EFFECTS OF AIR NAVIGATION TAX DUMPING WITHIN THE CURRENT EUROPEAN FRAMEWORK

Implementation of a Dijkstra's algorithm for flight plan optimization in the European environment

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Abstract

The planning of the flight route to be followed by each aircraft chartered is a relevant concern for airlines, as the efficiency of the calculated flight plan affects directly on operator's economical outcome. This efficiency can be assessed regarding different variables affecting the performance of the flight, as the distance flown, the fuel consumed or the time spent, and in many cases, a balance between all of them that allows a economically profitable flight plan is difficult to be found.

Therefore, the development of flight planning programs which are able to quantify the influence of each of these variables, and optimize the flight with respect to them, supposes a necessity to help airlines enhance its economical performance.

The scope of this work is then directed to the implementation of a software which allows the creation and optimization of flight routes to offer the user the possibility of easing the flight planning process. For this purpose, the structure and utilisation of the airspace in the European airspace must be understood, as well as the procedures and limitations imposed by the air traffic management and control systems. Along the process, the trade-off complexity between the different variables determining the economical efficiency of the flight plan is going to be comprehended.

The resulting flight planning program will be focused in offering a user-friendly environment which allows the quick and customized optimization of the desired flight plans. Through the solutions obtained from the program, it will be observed how optimizing with respect to some specific variables, like distance or time, yields immediate benefits directed to satisfy the user.

Finally, the adjustment of the flight plans proposed to the applying airspace regulations is going to be studied and implemented. With this, the output of the program will comply with the actual air navigation structure, and will provide then effective solutions adapted to the current airspace situation.

Acknowledgements

With this project, four intense years of my life come to an end. Years in which time has been availed and wasted but after which I can call myself an engineer. And for all of this, I have no other thoughts than of gratitude to a great little group of people.

First of all, my most sincere thanks to my father Francisco, my mother Carmen and my brother Alejandro, as they were the ones that had to put up with my numerous bad days without asking for anything in return.

Then, a further handful of thanks goes to the true friends that I found in my promotion. I always say that together, and thanks to each other, we pushed through each year of the degree with a lot of suffering and laughs. That is not enough to describe all the moments that we shared throughout these four years, including when they were hundreds of nautical miles apart.

A special mention is dedicated to Javier Lloret, who let me get involved in such an interesting project and has guided me in every step and detail of the process. Also, I would like to express my gratitude to Manuel Soler for his help in many aspects needed to complete the work.

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Chapter 1

Introduction

1.1 Introduction

Efficiency in the execution of the flight routes is a matter of deep concern affecting all the airlines operating within the European airspace. The cost that is incurred when fleeting an aircraft between a determined origin and destination, and the fact that an economical benefit should be obtained, oblige airlines to take into account and analyze to the detail all the variables that become involved when operating an specific flight route.

Therefore, it is understood that the efficiency of the execution of a flight route depends on a wide spectrum of factors affecting different characteristics of the flight. To name some of them, the more basic ones are the distance to be covered, the velocity of the flight, the overflight costs, the weight of the aircraft or the different flight levels used. Also, variables like the temperature distribution or the wind conditions play a relevant role. All of them have a huge impact on the economical performance of the chosen flight route.

In addition to this, it is important to notice that many of these factors influencing the economical performance of the flight are interconnected. For example, for an airline it is interesting, from the point of view of keeping a tight schedule or avoiding any compensations for delays or cancellations, to make every flight as fast as possible, but that would mean to increase the velocity of the flight, which would lead to a higher consumption of fuel and thus, an imbalance in costs could be produced. This interdependence between all the variables is the main factor influencing the establishment of determined flight routes, as finding the trade-off between the different advantages and disadvantages of every feature leads to the most efficient route in economical terms.

Then, for airlines it is important to have available tools that allow to carry out the analysis of different options to establish the routes that fit better their interests, which can vary depending on the situation. With the correct definition of their operative routes, any business fleeting aircraft on a determined day-to-day basis can have a competitive advantage by optimizing all its flight operations, mainly through a reduction in costs of different types.

1.2 State of the art

Nowadays, and over the past years, the computation and definition of the most efficient route in terms of costs for many of the airlines operating presently is carried out by two different algorithms, *Lido* and *Flight Plan Manager*, developed respectively by Lufthansa and Sabre Systems.

Lido, created by Lufthansa Systems, is an effective flight planning solution which identifies the best route within all the possible alternatives while taking current flight-related data into account. It then allows to optimize flight routes to enhance the performance regarding fuel consumption, cost or flying time.

The principal advantages that this commercial service, hired by airlines of different business models and sizes, provides are immediate savings in fuel, CO_2 emissions and costs. It achieves this through the analysis and optimization of every phase of the flight, together with an individual automation of the flight planning process. Thanks to this, Lido algorithm has been greatly used for the past 15 years, and currently it helps in the daily calculation and optimization of around 30.000 flights for over 60 airlines.

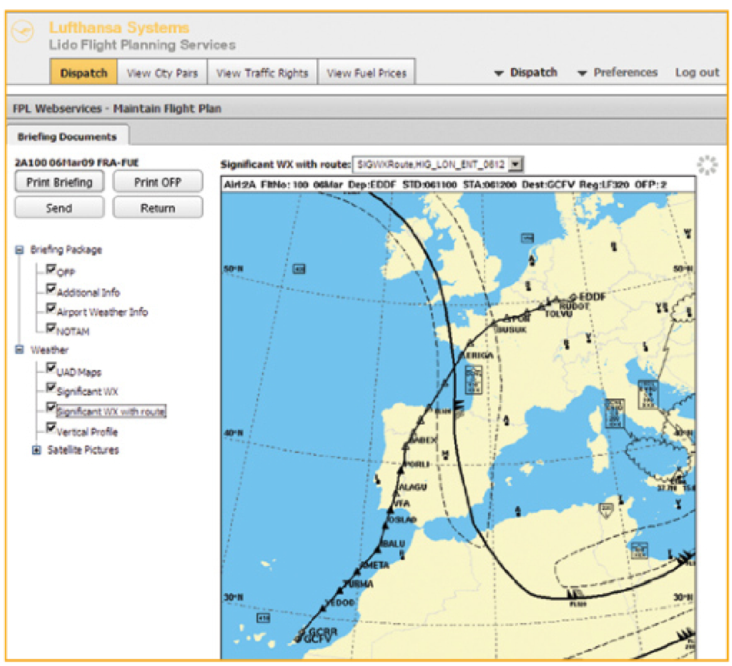


Figure 1.1: Lido Flight Planning Services GUI semblance.*Lido/FPLS: Reliable operational flight plans and dispatch support, Lufthansa Systems.*

Sabre's *Flight Plan Manager* is a similar tool that helps defining optimum, lowest-cost flight plans to increase the productivity of airline's operations. As it happens with *Lido*, the principal benefit for an airline through the use of this tool is that it allows to optimize flight plans to reduce fuel consumption. In addition to this, it offers a management of delays through a cost model that ensures the schedule integrity.

At the present time, these two solutions cover the majority of the market share related to flight plan automation programs, mainly because of two reasons. First, because they enhance the performance of airlines when it comes to the main concerns related to flight planning: optimizing burnt fuel, reducing CO_2 emissions, avoiding delays and automation of the process.

Secondly, in the flight planning process, they include all the vital factors that must be considered, as the weather conditions, NOTAM[1] handling, air space restrictions (which will be further explained in section 1.5), aircraft performance, ETOPS[2] accomplishments and real-time schedule information.

Therefore, over the past years, *Lido* and *Flight Plan Manager* have been the most used software solutions by the most important airlines (of all kind of types, either flag carriers or low-cost carriers) to plan and optimize their day-to-day operations, and serve as models for the creation and development of any algorithm related to the flight planning process.

As airspace design and regulations change continuously over the years, innovations to adapt to them are included continuously into the aforementioned flight planning software. One of the advances that is taking more importance nowadays is the further route, altitude and speed optimization through 4D trajectory-based approaches, which respond to the necessity of modernization of the airspace system. These improvements will be carried out through SESAR[3] in Europe and Next Generation Air Transportation System, also known as NextGen, in the United States. An example of the current researches in this topic is the recent release of an improved version of *Lido*, *Lido\Flight 4D*, which already includes modern 4D optimization (see [10]).

Apart from this, there are further researches and investigation trends that seek for taking full advantage of the air traffic management and airspace liberalization. One good example is the integration of disruption management[4] and flight planning to achieve an appropriate trade-off of passenger service with burnt fuel and additional operating costs incurred during recovery (for more information, see [11]).

Other research topics like integrated operations control and collaborative air traffic management also try to optimize the operating costs of airlines at different steps of the flight planning process.

[1] Notice to Airmen, notice filed with an aviation authority to alert aircraft pilots of potential hazards along a flight route

[2] Extended-range Twin-engine Operational Performance Standards

[3] Single European Sky Air traffic management Research Programme

[4] Process by which when a disruption occurs, airlines try to bring operations back on schedule as quickly as possible, while incurring minimal costs

1.3 Importance of flight plan optimization

As every commercial flight begins by the definition of a flight plan, its efficiency and optimization can lead to different benefits for airlines. First of all, each flight plan should ensure that each specific flight complies with the different operational regulations that are imposed in both the Air Traffic Management and Air Traffic Control phases.

Once this is clear, it must be understood that a flight plan includes basic information about the flight, as the departure and arrival points, the predetermined route to be followed, the type of flight (either under Instrumental Flight Rules (IFR) or Visual Flight Rules (VFR)), information about number of people and fuel on board, estimated time en route, and more.

Therefore, variations on many of the variables that compose the flight plan, which normally are subjected to aircraft performance, weather, restrictions on the route or on the schedule and operational constraints, can lead to a different level of efficiency on the execution of the flight. This efficiency is normally understood in terms of fuel costs, time-based costs, overflight costs and lost revenue from payload that can not be carried.

This is where the optimization of the flight plan plays an important role, as it enables the possibility of determining the optimal speed, route, altitude for every phase of the flight. It even can help in deciding the amount of fuel to be loaded on board. However, a huge amount of variables must be taken into account in order to execute a correct optimization, which converts this process in a complex one.

A flight plan can be taken as optimized when both the appropriate physics considerations, based on the specific aircraft performance, and the correspondent route restrictions imposed in both the ATM and ATC phases, together with the regulatory restrictions, have been used in its process of definition. This supposes that, due to the mathematical nature of all the variables, thousands of individual calculations are required to optimize all the different phases of the flight.

From this point, the enhancement of the optimization of the flight plan can help airlines in increasing their benefits by reducing fuel consumption and costs. For example, an accurate flight plan computation can provide the minimization of the additional fuel to be added by the crew in each flight, which results in immediate savings across the fleet of each airline.

Furthermore, the optimization of the flight plan can be directed to accomplish the scenario that better fits the airline's cost objectives, providing a very valuable operational flexibility. This would allow the airline to achieve different goals depending on the most profitable situation, which varies depending on each specific flight (routing of aircraft, scheduling, overflight, etc.).

1.4 Objective of this work

It is clear that the development of a tool that would allow airlines to optimize their flight plan depending on different variables has an evident commercial interest. For this purpose, a better understanding of the complexity of the airspace utilisation could lead to further advances in this matter.

Therefore, the basic idea is to create a user-friendly tool that optimizes a determined flight route in terms of distance and time. Initially, this supposes that the basic input introduced by the user is the origin and the destination point, but further real variables like the schedule of the flight or the type of aircraft used are also thought to be necessary.

Then, the optimization of the flight based on the characteristics mentioned before, introduced by the user, is intended to be carried out against different limitations that are present in real situations, as the properties of the airspace structure and the regulations imposed by air traffic management and control.

Once the idea is clear, some features should be required to the developed program. The most important one is that the obtaining of the optimized route should be carried out in a short time, as the conditions affecting the result change in the short term.

1.5 Theoretical background

When an aircraft covers a route between an origin and a destination, it travels within a determined controlled airspace using different specific navigation aids. To get a better understanding of the functioning of this system, it must be known that a controlled airspace is a portion of the atmosphere where there exists the necessity of having air traffic control managing the aircraft flying over it. Each country controls the airspace above its territory including its territorial waters (as expressed in the maritime laws), and thus, every country provides its national air traffic control over its sovereign airspace.

These airspaces normally are divided in different areas and zones. Some of these smaller zones impose limitations on the overflight of commercial aircraft, and thus, they suppose one of the first natural restrictions to be accounted for when planning a flight route.

Aircraft flying in controlled airspace must follow predetermined routes known as airways. An airway has no physical existence, and they start and end at a waypoint, containing maybe some other waypoints along the way. A waypoint can be understood as a point in the space determined by its coordinates, which identify an specific location, and they are basically used for the purpose of navigation. Therefore, an aircraft can pass from one airway to another at different waypoints, where airways cross and join.

A remarkable factor in the design of this net of airways is that the aeronautical charts describing it are usually updated and published every 28 days, coinciding with what is known as AIRAC[5] cycle. This AIRAC cycle

[5] Aeronautical Information Regulation And Control

Figure 1.2: Detail of the route network and structure of the spanish airspace. *Image extracted from Central Flow Management Unit Chart, EUROCONTROL.* [1]

is part of what is known as the Aeronautical Information Publication (AIP), a publication managed by each state's authority that contains aeronautical information needed for air navigation (regulations, procedures, etc.). Thus, each country publishes periodically an AIP containing normally three parts: GEN (General), ENR (En route) and AD (Aerodromes). Nowadays, it is not difficult to find the AIP for every country in an electronic format (normally, in PDF).

Therefore, it is clear that for the development of the program, the obtaining of all the regulations, procedures and features applying to the airspace structure, which can be found in the AIP of each state, is going to be a determinant factor.

However, the aforementioned regulations coming from the AIP are not the only ones that should be taken into account. The information published in the AIP is the one with a more general character and that normally lasts longer in time, as it contains thorough details of each feature.

Knowing this, there are some further documents and publications that are normally compatible and complementary to the AIP, and consequently, that completes the information offered in this publication. A good example of this is the RAD or Route Availability Document (see [12]), described by EUROCONTROL, the organism in charge of its issuing, as a common reference document containing the policies, procedures and descriptions for route and traffic orientation, including also route network and free airspace utilisation routes and availability. Therefore, the RAD is also necessary in any flight planning process, as it integrates both structural and ATFCM[6] requirements.

Together with the RAD, some more regulations with a temporal character should be accounted for. First, limitations established by the Conditional Routes, or CDR, shall also be used in any flight planning process. A Conditional Route can be understood as a non-permanent route or airway which can only be used under some specific conditions, normally related to schedule matters.

In addition, the relatively modern application of Flexible Use of Airspace (FUA) imposes some further regulations and restrictions. This ATM concept establishes that the use of determined zones of the airspace should not be limited to civil or military matters, but instead pleads for a flexible and adaptable airspace structure. The application of this concept supposes also the necessary establishment of determined regulations and limitations that again, must be taken into account in any flight planning process.

1.6 Characteristics and limitations of the model

A significant feature of the program that will be developed is that the optimization of the chosen flight route will only consider the cruise phase.

This means that most part of the climb, corresponding to the departure phase, and of the descent, corresponding to the approaching phase, will not be part of the optimization process.

When an aircraft takes off, it follows a departure procedure, known as Standard Instrument Departure or SID, that allows it to describe a trajectory from the airport to the appropriate waypoint on an airway, so that the entrance into the airways network is done in a safe and efficient manner. This trajectory, which is described while the aircraft climbs, is predetermined and defined by the air navigation authorities, hence, the optimization of the lateral profile in this phase is very limited.

The same happens when an aircraft starts the approaching phase to its destination, so it starts to descend and follows an arrival procedure. Also known as Standard Terminal Arrival Route or STAR, this procedure describes the opposite rules than the SID: marks the trajectory (both vertical and horizontal) from a waypoint which belongs to the airways network to the airport runway. Again, the optimization of the lateral profile of this flight phase is very limited due to the numerous restrictions that apply.

Therefore, as both the SID and STAR procedures will not be considered in the flight planning program, it can be said that the cruise phase, where the aircraft will be considered to maintain a constant flight level, is the one that will be under consideration in the development of the program.

Also, out of the scope of this work remains the optimization of the vertical profile described by the aircraft. Although the different altitudes that the aircraft uses to execute the flight constitute an important factor in its cost-efficiency, its consideration is left to further works related to this topic.

[6] Air Traffic Flow and Capacity Management

Therefore, this research is limited to the study of the lateral profile described by the aircraft.

In addition, it must be known that the program will be developed only considering the European airspace and not the global one, and that for some small-scale experiments, only the Spanish and Portuguese airspace are going to be considered.

Finally, it must be known that the model will be created using the MATLAB software, and all the graphical representations and technical data of the program that will be presented further on this work comes from the output of this software.

Chapter 2

Building the algorithm

Once the basic idea and the objectives of the work have been defined, it is time to start developing the program. Recalling what was expressed in the previous chapter, the aim to be achieved is to create a program that would help in the development of the flight planning process, and also allowing the user to optimize it regarding different factors under its decision.

2.1 Acquiring the necessary data

First, the necessary data background and basis to which the further operations and features should be included shall be acquired and prepared.

The process starts by being aware of what is the structure that will be necessary for the definition of the program. As was explained in section 1.5, the network of airways defined over the European airspace is the main driver of all the aircraft overflying these territories. Therefore, it would be interesting to find some kind of electronic information containing the description of these airways.

The easiest way of defining these airways is by obtaining the properties of each waypoint in the European airspace, as they constitute the connection between the different airways. Furthermore, as the interest lies in developing the program for the lateral profile of the flight, with only the geographical coordinates of every waypoint, the required network of air routes that it is actually being used could be totally defined.

However, it is not easy to access this information in an electronic format that allows the introduction of the data in a programming platform. Every country, through the issuing of its national Aeronautical Information Publication, keeps a database of every waypoint and airway belonging to its sovereign airspace. However, due to the need of the features of the whole European airspace, another type of source should be accessed.

EUROCONTROL, or European Organisation for the Safety of Air Navigation, is an international civil organization which basically coordinates air traffic control and air traffic management for many member states in Europe, working collaboratively with them. One of its main functions is to provide a centralized access for the Aeronautical Information Service (AIS)[1], mainly through its EAD[2] support.

EAD serves then as the database of aeronautical information of all the member states of EUROCONTROL. Therefore, apart from giving professional support to all airspace users, it enables the access to a huge amount of aeronautical data for academic use, interesting from many points of view.

Specifically one of EAD's services, OneSky Online (see [13]), gives access through a registration process to a database known as DDR2, or Demand Data Repository (more in [14]). In this repository, different interesting sets of data can be encountered.

As was explained in section 1.5, the aeronautical data that will be used for the development of the program is updated periodically (every 28 days) following what is known as AIRAC cycle. Therefore, this information, basically the one contained in the Aeronautical Information Publication of every member state (with some minor differences), can be found in one of the datasets available at DDR2, particularly in the Airspace Environment Datasets tab.

More specifically, every dataset of interest is identified and classified by the corresponding AIRAC cycle under application. This means that the data that is obtained through this service has to be downloaded periodically following the AIRAC cycle, as the information included in it is updated and changed with every cycle.

The automation of the periodic downloading process of the most recent dataset would be an important feature to implement in the program, as it would allow to have the most updated version of the information and would avoid to have any miscalculation in the flight planning process; as for example, an airway that is open in the most recent AIRAC cycle can be closed in the following one due to various reasons.

However, the services that the EAD support concedes to the public access of a regular user do not include the automatic connection and downloading of the datasets of interest. Therefore, the fact that all the identification and downloading process of the basic AIP information is manual is an important fact to be improved. There exists some possibilities to automatize this process, but all of them entails the contract of a professional service.

Even this option was considered, as a contract between the Universidad Carlos III de Madrid and EUROCONTROL was established in order to have access to the EAD Test Systems. Through this account in MyEAD services (Ref. [15]), access to the ITP Service Desk (Ref. [16]) was also granted, but in neither of both services the required automatic connection could be established. Therefore, despite of all efforts made in this direction, it was not possible to automatize the acquirement of trustworthy AIP information with every AIRAC

[1]Service in charge of regulating the flow of information necessary for the safety and efficiency of international air navigation. Its main function consists on ensuring the publishing of the AIP, the Aeronautical Information Circulars (AIC) and the NOTAMs.

[2]European AIS Database

cycle, so up to this point, it stands as a manual process.

Regarding the available dataset, it contains the data necessary for the development of the program: includes the definition of every waypoint in the European airspace through its geographical coordinates (longitude and latitude, altitude is not included), together with every connection between waypoints. Therefore, with this, apart from having the possibility of defining the whole network of waypoints, also the sense of the airways can be known.

This is important because the use of the connection between two waypoints (A and B) defining an airway or a segment of an airway can be enabled in three different ways: allowing the flow of aircraft from A to B, from B to A, or allowing both. When developing the program, it will be important to define the algorithm in order to respect the configuration of these connections.

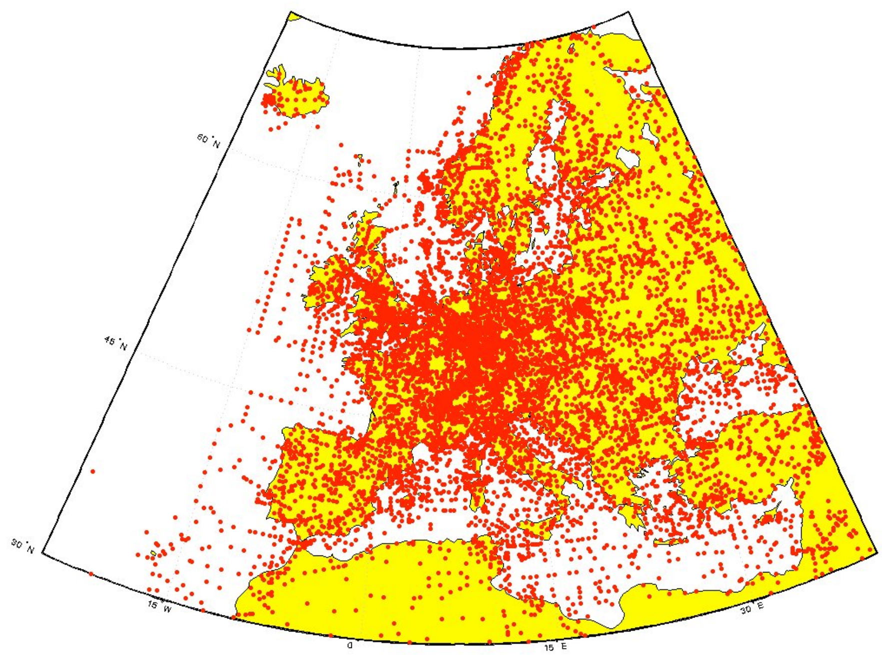


Figure 2.1: Implementation of the waypoints network in the European airspace

It is essential to understand that the connections defined in the downloaded data only include the limitations established in the AIP. Therefore, the waypoints network that can be observed in Figure 2.1 is the basic configuration of the airspace, with only the restrictions imposed by natural limits or by long-term conditions (permanently closed airways, lack of air navigation services in certain sectors, etc.).

This means that there is a lack of airspace limitations imposed by further regulatory documents, like the mentioned before Route Availability Document, consisting basically in scheduling the availability of certain routes (for example, closing a certain airspace sector due to military use) and establishing short-term changes.

However, for the following steps, the short term changes included in the regulatory documents mentioned in section 1.5 are going to be put aside, as they are not available in the most complete datasets found in DDR2. In further sections, it is going to be seen how to include these additional restrictions.

Upper and lower airspace limitations

Throughout Europe, the most basic subdivision of the airspace, defined by ICAO[3], consists on the lower airspace, which is below FL245[4], and the upper airspace, which logically is above FL245.

Normally, an aircraft covering an international flight will take off and climb through the lower airspace until a determined flight level for the cruise phase is achieved on the upper airspace, and the aircraft will not leave it until the approach phase starts. Therefore, it is normal that an important part of the flight route is described through the upper airspace.

This basic information of the airspace structure is relevant because the waypoints conforming the airways network are defined either for the lower or for the upper airspace, or even for both.

However, in all the datasets downloaded from the aforementioned sources, the database of waypoints does not include the classification of the waypoints depending on the airspace class in which they are defined.

As in this work the interest lies on the lateral profile described by the aircraft, this fact is not going to be taken into account, and every waypoint will be considered whether it is defined for the lower or for the upper airspace.

In any case, for further research and advance on this topic, when the vertical profile of the aircraft is under consideration, developing the algorithm to differentiate the waypoints depending on its airspace class definition would be a necessary feature.

2.2 Creating the algorithm

After implementing the necessary data to define the network of airways that is used by aircraft to navigate, the program is ready to start finding the desired routes introduced by the user.

For this purpose, as seen in 1.4, the first objective to be fulfilled by the program is to find the optimum route in terms of distance with only the origin

[3]International Civil Aviation Organization

[4]FL: Flight level, a specific barometric pressure expressed in terms of nominal or pressure altitude (in hundreds of feet). Thus, when an aircraft uses FL245, it means that its pressure altitude is of 24500 feet.

and the destination waypoints as input. Thus, the algorithm has to compute all the possible paths and find the shortest one. This should be done by analysing every step of the flight to see which one is the most efficient in terms of distance. In this way, the sequence of waypoints to be followed should be obtained.

As it can be guessed, the computation process for just a national flight entails a huge amount of calculations to compute the different trajectory possibilities, plus the election of the most interesting one. It must be borne in mind that for the whole European airspace there are around 25,000 waypoints under consideration, so the amount of combinations for a long flight is way too large.

However, the output of the program must be shown to the user relatively quickly, so that the amount of calculations mentioned above should be optimized in order to minimize the computation time.

Knowing this, the solution proposed in this work is to use what it is known as Dijkstra's algorithm, as its development can provide all the different features that are required for the flight planning tool in terms of computation.

2.2.1 Dijkstra's algorithm

Dijkstra's algorithm is a programming tool that helps in finding the solution of the single-source shortest path problem that is present in the flight planning process.

This type of problem consists on finding the shortest paths to all the nodes present in the airways network (the waypoints) from a single designated source or origin waypoint. In addition to this, an specific destination can be determined and used as input as well, establishing a desired objective for the algorithm calculations.

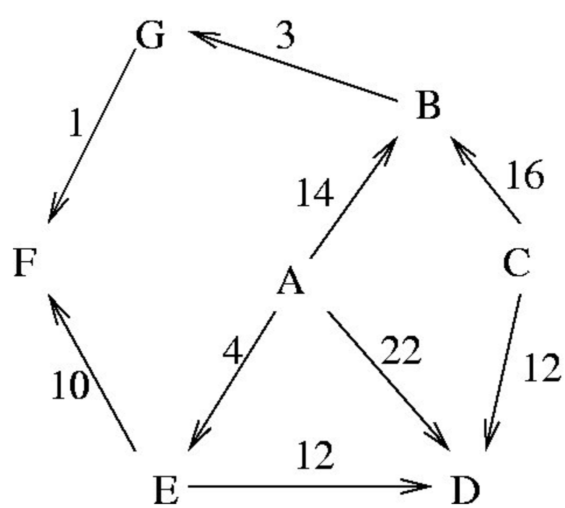


Figure 2.2: Example of a simplified graph where Dijkstra's algorithm can be used. *Example figure, Software Workshop Java: Dijkstra's algorithm.* [2]

As it can be observed in Figure 2.2, and as will be applied for the flight planning problem, the graph or network under consideration will have weighted edges which represent the different airways or segments of airways.

Therefore, the shortest path between two determined vertices or nodes will be the one that follows the least weighted edges from node to node.

Mathematically, the problem can be posed as:

$$\text{Let} \quad G = (V, E) \quad \text{where} \tag{2.1}$$

- V is the set of vertices or nodes
- E is the set of edges or segments

It must be clarified that the weights of the segments E must be non-negative and different from zero. For the purpose of the design of the program, the weights of the edges can represent the nautical miles between each waypoint, or as it will be seen further on, the cruising time between waypoints.

Thus, the length of a path starting in vertex v_0 and finishing in vertex v_n, so that $p = v_0, v_1, ..., v_n$, will be the sum of the weights of the constituent edges. Being the interval defined as $u(v_0, v_n)$, we find the length of the covered path as:

$$length(p) = \delta(v_0, v_n) = \sum_{i=1}^{n} u(v_{i-1}, v_i) \tag{2.2}$$

where every single vertex or node $v_i \in V$.

A simple example using Figure 2.2 can be exposed to understand better the functioning of the algorithm and to see the output obtained.

If it was desired to go from node A to node G, different paths could be undertaken. The program is thought to analyze them all and to see which is the most efficient in terms of edge's weight, that is, the path with the smallest length $\delta(A, G)$.

The output provided by the algorithm would be:

- Value: $\delta(A, G) = 15$
- Path: A, E, F, G

It is clear that the use of this type of algorithm is very beneficial for flight planning purposes, as the output allows the user to know which is the path to be followed (in actual terms, the sequence of waypoints) as well as the distance that supposes taking that path (for example, knowing the amount of nautical miles to be covered, a better calculation of the fuel to be used can be carried out).

Relaxation

For a multinodal structure like the one describing the airspace structure, where a huge amount of nodes are under consideration (as can be observed in Figure 2.1), it is important to implant a more efficient behaviour to Dijkstra's algorithm through the use of the relaxation concept.

Relaxation is the process by which when processing the step from a vertex v_i to a vertex v_{i+1} for all vertices $v_{i+1} \in Adj[v_i]$, an estimate $d[v_{i+1}]$ of the shortest path from the single source v_0 to every vertex v_{i+1} is maintained. Therefore, always applies:

$$d[v_{i+1}] \geq \delta(v_0, v_{i+1}) \tag{2.3}$$

Then, initially it should be established that $d[v_0] = 0$, and the rest of estimates $d[v_{i+1}] = \infty$. It will be also infinite in the case that no paths are calculated yet. That is, at the beginning of the computation of each step, the estimate $d[v_{i+1}]$ will automatically be infinite, as no path has been explored yet.

At the beginning of each step, the algorithm processes the length of the path for every different adjacent vertex one by one, so that for each vertex, a new path from v_0 to v_{i+1} is found.

Relaxation then imposes that if the length of this new path from v_0 to v_{i+1} is shorter than the applying estimate $d[v_{i+1}]$ (equal to infinite at the beginning of the step), this estimate $d[v_{i+1}]$ is then updated to the length of this new path.

The use of the aforementioned automatic assignation of infinite values to the estimate at the start of the step also serves to ease the checking of the existence of a path: if the estimate $d[v_{i+1}]$ has a finite value, a path exists.

This is the formal definition of the relaxation concept, but in order to understand it better, a practical example can be performed. To do so, the graph shown in Figure 2.3 can be used.

For the sake of simplicity, the objective will be to find the less-weighted path from S to B. In the first step, all nodes will be assigned an estimate equal to infinity. Then, iteratively, the algorithm computes which nodes are neighbours of S. It is seen that the weight to A is 10, and the weight to C is 5. These are smaller than the previous estimates for A and C, which were equal to infinity, so these estimates are updated.

Now, the node with the smallest estimate is chosen, which is C. This node is connected to A, B, and D. Therefore, the algorithm will compute every possible way following an iterative process:

- The algorithm will start by choosing the smallest following estimate, which is D, with a total estimate of $5 + 2 = 7$. Then, to node B, the total weight for the route will be $7 + 6 = 13$. This is smaller than the actual estimate of B, which is infinite, so the estimate of B is updated to 13. A path exists.

- To node B, the ultimate destination, C is connected with a weight of 9, which constitutes a total weight from S to B of $5 + 9 = 14$. This estimate is higher than the previous estimate of B, which is equal to 13, so the estimate of B is not updated and the path is discarded.

- To node A, the weight is 3, which summed with 5 yields a total weight of 8. This is smaller than the previous estimate of A, which was 10, so the estimate of A is updated to 8. Then, A is connected only to B with a weight of 1, supposing a total weight from S to B of 9. This is lower than the current estimate of B, which is 13, so that the estimate of B is updated to 9, constituting the total weight of the path from S to B.

The total weight of the path S-C-A-B is already smaller than the connection S-A, so any further computation following the connection S-A is going to provide higher weights, and thus, they will be discarded. With this, the functioning of the algorithm with the concept of relaxation is practically explained.

Directed structure

The airways structure in the European airspace is determined by the junctions and connections of the waypoints defined through geographic coordinates. As was expressed in section 2.1, two waypoints can be joined in three different configurations which determine the usage of the specific airway or segment of airway.

As it can be seen in Figure 2.3, depending on the availability of the connection between waypoints, the different paths that can be followed change importantly.

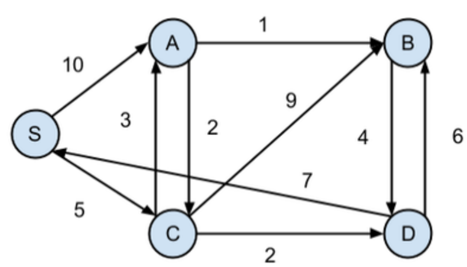


Figure 2.3: Example of a nodal structure with different connections configurations. *Dijkstra' Algorithm - Example, Siddartha Reddy.* [3]

These discrepancies in the junctions of the waypoints come from the natural limitations of the airspace structure and from the application of different regulations.

Consequently, the fact that the algorithm takes into account the direction of the connections acquires a huge relevance, as it is a very influencing factor determining the shortest path. Then, it is clear that the Dijkstra's algorithm should be directed, that means, it should take into account the definition of the sense of the connection between each pair of joint waypoints.

2.3 Integrating the algorithm with the model

The definition of the algorithm's functioning in the previous section made clear that the shortest path between an origin and a destination can be found for a multinodal directed graph. Precisely, that is the basic structure of the airways network, so that the algorithm fits the model.

Therefore, the only input left necessary to create a basic flight planning tool is the definition of the weights of the edges. As it was exposed in section 2.2.1, for the case of finding the shortest route in terms of distance, the weights of the edges between two waypoints can be established as the geographic distance between them. Using this model is a logical thing to do, as the algorithm will seek automatically for the edges with the smallest weight, that is, for the shortest connections.

2.3.1 Calculating orthodromic distances

The orthodromic distance can be understood as the shortest path between two points located on the surface of the Earth, so that is the great circle's arc (the one with the shortest length) that joins them.

In the Euclidean space that is normally used, the shortest way to go from a point to another is to follow the straight line that joins them. However, employing a non-Euclidean geometry, and using instead an orthographic view to take into account the curvature of the planet Earth, this straight line is seen now to be a great-circle arc, as can be observed in Figure 2.4.

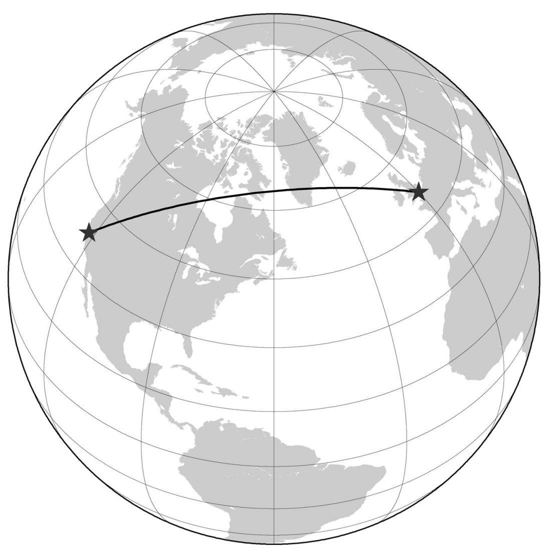


Figure 2.4: Shortest orthodromic distance between San Francisco and London seen on an orthographic projection. *Figure 3-32, Mapping Hacks: Tips and Tools for Electronic Cartography.* [4]

The great-circle distance between two points can then be understood as the circle of the sphere, with its center coincident with the center of the Earth, that joins both points.

Therefore, these two points divide the great circle in two different arcs, one longer than the other (except in the case that the points are opposite to each other, so that both arcs would have the same length and the points would be known as antipodal points).

Then, the length of the shorter arc is the one interesting for this work, as it is the great-circle distance between the two points.

Mathematical formulation

From the datasets downloaded from EUROCONTROL's DDR2, as was seen in section 2.1, the definition of the airways network was available through the determination of the geographical location of each of the waypoints conforming it.

Consequently, the information available is the definition of the latitude and longitude of each of the waypoints, which will be enough to determine the distance between each of them.

For this purpose, orthodromics theory is going to be used. More specifically, the spherical law of the cosines is the tool that fits better, as it establishes that:

$$D = arccos[sin(l) \cdot sin(l') + cos(l) \cdot cos(l') \cdot cos(\Delta L)] \tag{2.4}$$

Where we can define each of the variables as:

- D is the orthodromic distance between two waypoints, A and B.
- l and l' are the latitudes of waypoints A and B respectively.
- ΔL is the difference between the longitudes of each waypoint.

It is important to bear in mind that for this formula to work, both latitude and longitude should be expressed in decimal degrees notation[5].

To convert this distance to nautical miles (the classical notation used for expressing distances in the aeronautical world), it must be known that D is obtained in degrees, and when working in nautical miles, it must be expressed in minutes. Therefore, the resulting S obtained from equation (2.4) must be multiplied by 60.

With this, and after applying this formula for every connection described on the downloaded dataset, all the inputs needed to complete the model are properly defined, so now the flight planning tool can start the computations.

[5]Decimal degrees notation is a type of geographic coordinate system which expresses latitude and longitude as decimal fractions, and is an alternative to the Degrees, Minutes and Seconds (DMS) notation. For example, Adolfo Suárez Madrid-Barajas Reference Point (ARP) expressed in decimal degrees notation is 40.2820ºN 3.3339ºW.

2.4 Finding the shortest route

The flight planning tool that this work aims to build has already all the necessary information and data to find the shortest route between two points defined by the user.

As a reminder, the airways network used for this first steps does not include the short term regulations that were explained in section 1.5 (in further steps, actions are going to be taken regarding this fact). However, it does take into account the natural limitations, as well as the definition of the proper use of the airways (allowed directions) included in the correspondent dataset used.

With respect to this, for the following examples, and for the ones that will be shown further on, it has been decided to use the information correspondent to the dataset of the AIRAC cycle 1410[6], as it was the most recent one available at the time the algorithm was being developed.

2.4.1 Algorithm's output

With the waypoints network established through its geographical coordinates and with the connections defined through the orthodromic calculations shown in section 2.3.1, the only thing to worry about left is the presentation of the output from the algorithm.

As seen in section 2.2.1, both the path to be followed and the sum of the weights followed, that is, the sequence of waypoints and the distance covered, are the natural output coming from the use of Dijkstra's algorithm. Therefore, it will be important to show these data clearly and quickly to the user.

In addition to this, it is also interesting to present this information in a more graphical manner, mainly through the representation of the path in a map. This representation should highlight the waypoints to be followed, as well as the origin and the destination, so that the user can acknowledge easily the information that is needed.

Map projection

In order to embody all the data relative to the specific location of the waypoints in a graphic representation of the Europe's map, a proper projection should be used. For this purpose, the Lambert conformal conic projection[7] is used to represent the different territories. Therefore, the waypoints are projected taking into account this representation.

This type of conical map projection is widely used in aeronautical charts and mapping systems, basically because it helps in approximating great-circle routes (seen in 2.3.1) between endpoints for typical flying distances. The map presented in Figure 2.1 already uses this projection, and in Figure 2.5 can also be observed.

[6] AIRAC cycle 1410 applied from 18.09.2014 to 15.10.2014

[7] More information regarding Lambert conformal conic projection can be found in [17]

Figure 2.5: Representation of world's map using the Lambert conformal conic projection. *Lambert conformal conic projection, Wikipedia Commons.* [5]

2.4.2 Actual results

In order to check if the model proposed works effectively, some cases should be run so that the output can be analyzed. For this purpose, first, some flight routes are going to be introduced only for the Iberian Peninsula airspace, as it would be easy to proof that the algorithm is working well in a small scale model.

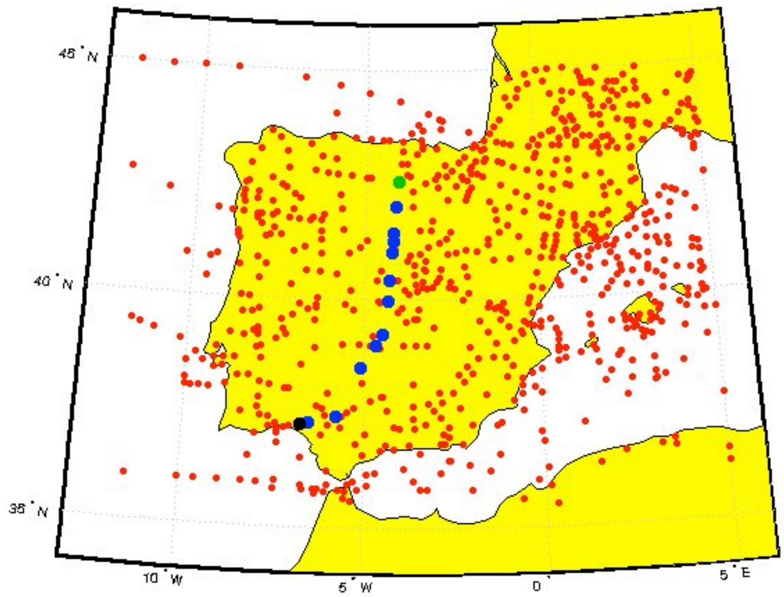
For the examples that are going to be shown below, as well as for further cases, the origin and the destination waypoints, that need to be introduced by the user, are going to be highlighted with green and black colors respectively. The waypoints in the midway that complete the sequence to be followed are marked in blue, while the rest of waypoints that should not be followed can be seen in red.

Then, in order to run the first case, the only thing needed to be defined is the desired origin and destination point. For this, looking in the en-route aeronautical charts present in the Aeronautical Information Publication of ENAIRE[8], two random waypoints can be looked up and used as input for the flight planning tool.

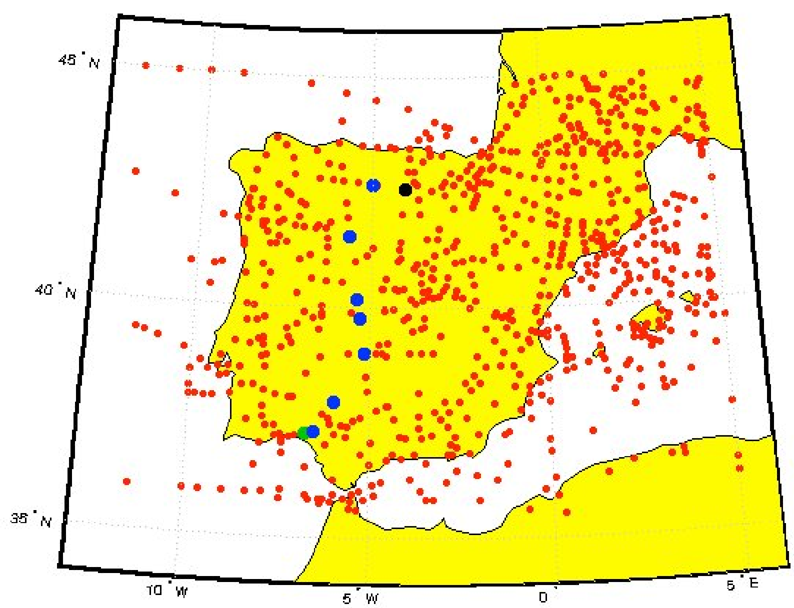
A suitable case for showing the first example of the algorithm's output could be the flight plan covering the route from waypoint *RATAS* to waypoint *ONUBA*. Also, for the sake of checking if the natural limitations regarding the direction and use of airways are being applied as they should, it is interesting to see the reverse route, from *ONUBA* to *RATAS*.

Thinking logically, it is expected that not the same waypoints will be followed in each case, and thus, the distance covered will also be different.

[8]ENAIRE, former AENA, is the public organization in charge of managing the majority of airports in Spain, and is also the body responsible of providing the different services for Air Traffic Control in the Spanish airspace. Thus, one of its responsibilities is to manage the Air Information Service.



(a) *RATAS-ONUBA*



(b) *ONUBA-RATAS*

Figure 2.6: Graphic representations of the flight plans.

```
Path =

    'RATAS'
    'NEA'
    'ODAPA'
    'ORBIS'
    'DISKO'
    'KALMA'
    'TLD'
    'MONTO'
    'MOLIN'
    'HIJ'
    'SVL'
    'PIMUR'
    'ONUBA'

Distance: 373 nautical miles.
```

(a) *RATAS-ONUBA*

```
Path =

    'ONUBA'
    'PIMUR'
    'OXACA'
    'PARKA'
    'MELON'
    'ZORBA'
    'ZMR'
    'NUBLO'
    'RATAS'

Distance: 405 nautical miles.
```

(b) *ONUBA-RATAS*

Figure 2.7: Flight plans technical information.

In Figures 2.7 and 2.6, the flight plans proposed by the algorithm for both cases can be observed.

The first thing that should be remarked is that the algorithm seems to work properly. Checking merely the results obtained with the aforementioned en-route aeronautical charts provided by ENAIRE's AIS, it can be seen that the path followed in both cases is first, possible to be followed, and second, logical.

Then, as it was previously mentioned, obvious differences can be observed between both cases. For the north-south flow, that is, for the *RATAS-ONUBA* route, it is seen that more waypoints need to be visited to complete the flight plan, although the distance that the aircraft needs to cover for this purpose is significantly smaller than in the reverse case (32 nautical miles less). However, for this longer case of the *ONUBA-RATAS* route, the number of waypoints used is smaller than in the other flight plan.

These differences can be explained due to the facts exposed in section 2.2.1, and here is where lies the importance of defining a directed Dijkstra's algorithm, as the direction in which an airway is defined has a huge relevance in the flight planning process. This has been shown with the output observable in Figures 2.6 and 2.7, where it is clear that changing the direction in which the aircraft flies (in these cases, headed south-west or headed north-east) varies importantly the path to be followed in order to minimize the distance to be covered.

A little detail that can also be noticed in Figure 2.7, is that some of the components of the sequence of the flight plan are composed by five letters and others by three letters. The formers represent the already known and explained waypoints, while the latters represent the VORs[9], which can also be used during the cruise phase of a commercial flight.

[9]VOR: VHF Omni Directional Radio Range, is a radio navigation aid which help aircraft determine their position and stay on course through radio signals emitted by radio beacons. More information on the functioning and utility of VORs can be found in [18].

The main difference in order to distinguish between waypoints and VORs is that the first ones are not a physical entity, they are just imaginary points represented by their geographical coordinates; while VORs are physical ground stations emitting radio signals.

Results in the European airspace

Proven that the algorithm seems to work correctly in the small scale of the Iberian Peninsula airspace, it is time to extrapolate that work to the whole European territory.

The main problem that can arise in this step is that the algorithm may not be efficient enough to handle all the calculations needed for a long flight, or that the processing time to make all these computations is too high for an effective flight planning tool.

To check this, the shortest route joining the waypoint *LOTEE* with the VOR *IST* (in Figure 2.8), and again, its reverse route *IST-LOTEE* (in Figure 2.9), is going to be found. This time, and opposite to the previous case, the algorithm will process a west-east flow across a big part of Europe.

First, regarding the processing time of the algorithm to complete all the calculations and show the output, it has been seen that takes around 5 seconds to provide the path or sequence of waypoints, together with the distance covered, and only 3 seconds more to show the graphic representation of the trajectory to be described.

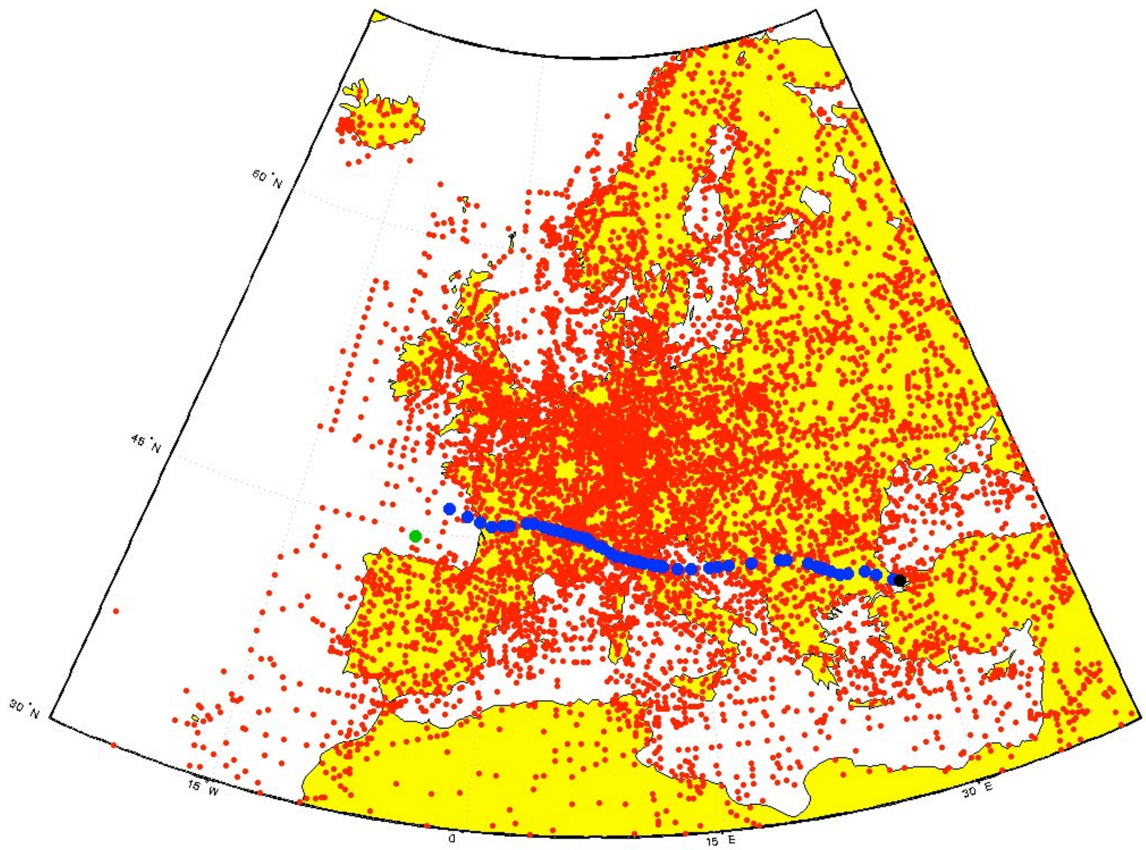
Taking into account that the flight routes used for these examples are considerably long (1601 and 1607 nautical miles, with 57 and 47 waypoints under consideration for each flight respectively), it can be stated that the algorithm works effectively and efficiently based on its acceptable processing time.

With respect to the output observable in Figures 2.8 and 2.9, in a first approach it can be said that both routes seem to follow a logical path, and that also the east-west flows seem to be computed correctly.

It was interesting to check this because as it can be observed in both graphic representations, in the central-European airspace zone, the density of waypoints increases considerably with respect to other areas. This means that also the number of connections grows, and thus, with it, the difficulty in finding the optimal route.

Comparing both cases for the purpose of checking the correct functioning of the directed algorithm, it must be remarked that the difference in distance between the two flight routes is very small compared to the actual distance to be covered for both cases (6 nautical miles, which is a rough 0.4% of difference). This gets even more interesting when checking that the sequence of waypoints for both cases is, in a majority, totally different.

These data contrast with the results obtained for the case in the small scale shown in Figures 2.6 and 2.7, where, although the sequence of waypoints was also dissimilar between the opposite routes, it was found a 8.5% of difference in distance to be covered (with respect to the shortest distance, 373 nautical miles) for a much shorter flight route.

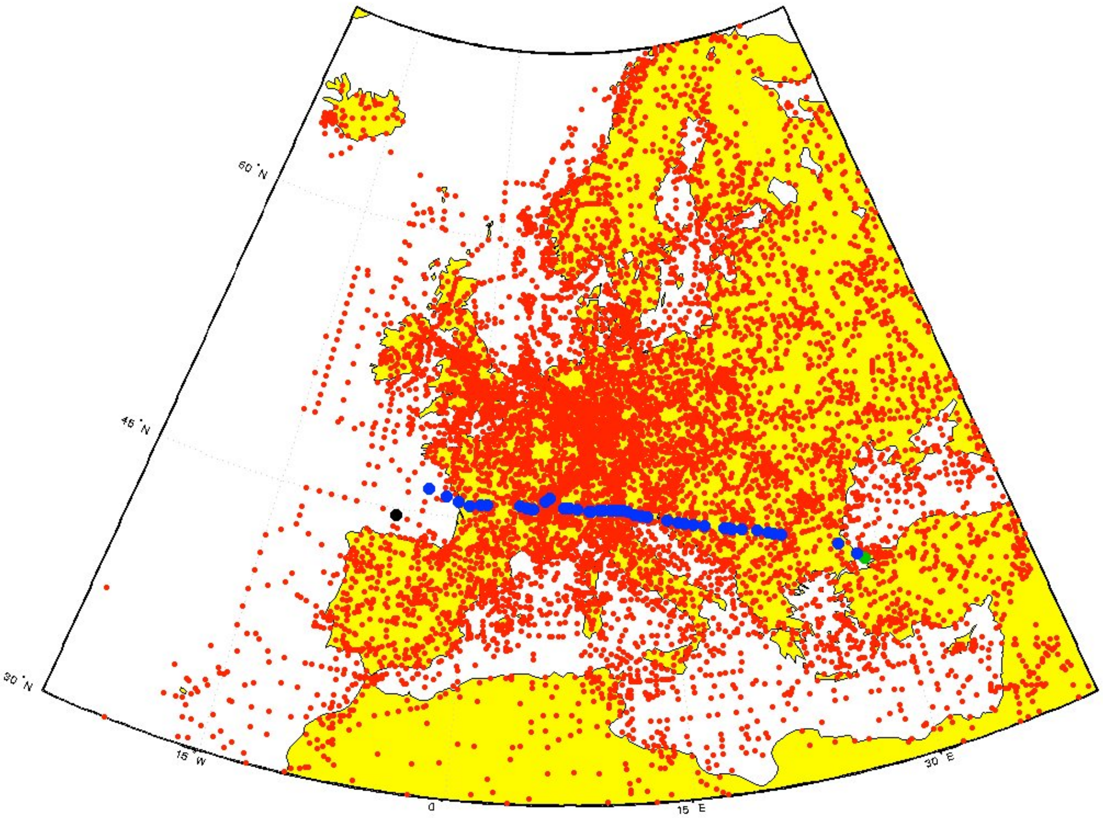



```
Path =

    'LOTEE'
    'NOVAN'
    'GODEM'
    'DILRA'
    'CNA'
    'FOUCO'
    'LMG'
    'LASEV'
    'VALKU'
    'TIS'
    'BELEP'
    'MADOT'
    'MEBAK'
    'RUSIT'
    'GIPNO'
    'BALSI'
    'GIGUS'
    'KINES'
    'MEDAM'
    'ATMAD'
    'NITAM'
    'KODOK'
    'TOP'
    'ASTOR'
    'TESTO'
    'GEN'
    'KALMO'
    'MIVKI'
    'BEROK'
    'RUXOL'
    'BALUK'
    'FRZ'
    'VABMO'
    'BAGNO'
    'PIDEP'
    'LIKNO'
    'ASDOR'
    'ANC'
    'TORPO'
    'UMSON'
    'SPL'
    'DIXUM'
    'OSLUD'
    'RAMAP'
    'GINAM'
    'NISVA'
    'SOF'
    'PIDOR'
    'WAK'
    'LARAT'
    'RUMEN'
    'PDV'
    'ROVDO'
    'ADORU'
    'SERCE'
    'TIRER'
    'IST'

Distance: 1601 nautical miles.
```

Figure 2.8: Flight plan information for route *LOTEE-IST*.




```
Path =

    'IST'
    'FENER'
    'VADEN'
    'OGOTA'
    'DOLAP'
    'OBLAK'
    'RAVAK'
    'NANER'
    'KOSIV'
    'KUKUN'
    'VEBAR'
    'BOSNA'
    'NAVSU'
    'SUDIM'
    'KOREX'
    'OBALA'
    'NAKIT'
    'ROTAR'
    'AKADO'
    'LAPAB'
    'VIC'
    'VADIK'
    'IBUGO'
    'ADOSA'
    'IDREK'
    'ELTAR'
    'OSKOR'
    'LEGLO'
    'DESIP'
    'SRN'
    'OMETO'
    'TERSI'
    'AOSTA'
    'BANKO'
    'MILPA'
    'NINTU'
    'MEBAK'
    'MADOT'
    'BELEP'
    'TIS'
    'LMG'
    'FOUCO'
    'CNA'
    'DILRA'
    'GODEM'
    'NOVAN'
    'LOTEE'

Distance: 1607 nautical miles.
```

Figure 2.9: Flight plan information for route *IST-LOTEE*.

The explanation to these facts can be based on the aforementioned increase in the density of waypoints available through a big part of the flight route under consideration. A larger number of available connections can make that a more optimal route can be found, basically due to this increase of options available. In addition to this, this behaviour can be justified with the normal ATM and ATC procedures followed by actual airlines nowadays, as usually aircraft flying headed west do not follow the same path that aircraft flying headed east (as well as for any pair of opposite directions, north-south, etc.).

Conclusions

The examples shown in the previous sections serve as a proof to be sure about the efficient character of the output provided by the algorithm, and also helps in stating that the limitations included in the basic dataset used are being taken into account when performing the calculations.

This correct performance of the algorithm establishes the base for further improvements that need to be included in the model in the following steps. In any case, the flight planning program proposed does already offer the possibility of effectively optimize flight routes all across Europe in terms of distance.

Chapter 3

Enhancing the model

The flight planning tool developed until this point is capable of optimizing a determined flight plan in terms of distance to be covered. However, further features should be integrated in this model, mainly related to additional options for optimizing the flight plan desired by the user. Also, asking for further input to be introduced by the user can help in providing a more specific application of the algorithm, so that the use of the program becomes more useful.

An effective way of improving the experience with the program for the user is offering further features. Due to the various factors influencing the operations of an airline, providing only the possibility of optimizing with respect to the flying distance supposes a limited model. This is because an airline can be interested in different factors affecting the flight, as for example, flying over determined airspaces to reduce the overflight costs, although it can suppose some extra nautical miles to be covered.

Therefore, knowing the model of computation of the algorithm, additional options should be integrated in order to obtain a more complete flight planning tool which could in fact be actually useful for any airline.

3.1 Reducing the flight time

The time of flight that an aircraft needs to complete a flight route is one of the most important variables affecting the efficiency of the flight. The more time that the aircraft spends in the air, the more fuel that it burns, the more CO_2 is emitted, and the more possibilities exist that the aircraft does not comply with its schedule.

When covering a flight route, there are various reasons that can oblige the aircraft to keep more time than expected in the air. A flight can be detoured due to bad weather, military airspace scheduling limitations, congestions and more, so that this additional flight time has an impact in the whole system.

First, all these factors have an important influence on the economical efficiency of airlines. And not only on these agents, because due to the increase in the demand of air transportation, congestion of the airspace provoked by commercial aircraft is becoming a relevant problem that air traffic management and air traffic control are suffering. Therefore, it is clear that an optimization in the flight planning process related to the flight time is an important feature to be developed.

Nowadays, there are different researches which try to find ways to reduce the time of flight, and not necessarily related to the flight planning phase. The two more important ongoing initiatives related to this topic are Next Generation Air Transportation System, also known as NextGen (see [19]), and SESAR[1].

NextGen is being implemented in the United States, and it basically aims to manage the air traffic control systems based on satellite methods, instead of based on ground systems, as is done nowadays. With this technology, a reduction in fuel and time costs[2], together with shorter routes, less congestions and many other benefits are supposed to become effective.

SESAR is its European counterpart, as although the composition of the project is different than the one for NextGen, the objectives are very similar. Therefore, it is clear that there are undergoing global actions related to air traffic management and control that aim to improve the performance in terms of flight time, as it will bring benefits to the whole system.

Quantifying these benefits, SESAR is expected by 2020 to help saving 8 to 14 minutes, 300 to 500 kg of fuel and 948 to 1575 kg of CO_2 emissions per flight. On the other side, NextGen estimates that by 2018 will reduce the spent of aviation fuel by 1.4 billion gallons, the CO_2 emissions by 14 million tons and help saving 23 million dollars related to time costs.

As explained in previous sections, these numbers are all related, as reducing the flight time and the congestions it provokes suppose an immediate reduction in fuel an emissions. For example, IATA[3] estimates that only by reducing globally one minute the duration of each flight, 4.8 million tones of CO_2 would be saved every year, as explained in [22].

These figures help to illustrate that an optimization related to the flight time will have an important impact on the economical efficiency of each independent flight, and a global influence on the way the air traffic system is operating nowadays.

3.2 Optimizing flight routes

Despite all the information seen in 3.1, in this work the scope is limited to the flight planning process. The initiatives seen are thought to improve the way in which air traffic management and control are being carried out, but now the attention should be centered on how an optimum flight plan can help in reducing all type of time-based costs.

[1]Single European Sky Air traffic management Research. More information on [20].

[2]NextGen is supposed to enhance the performance related to flight times, as it can be seen in [21].

[3]IATA: International Air Transport Association

For this purpose, it should be known that an optimum route depends entirely on the actual conditions determining its development. Optimum route will be understood in this context as the one that provides the less time-based costs. Therefore, it can be stated that these time-based costs, dependent on the flight conditions, can not be simply determined, as they are dynamic.

The principal factors affecting the time-based costs that should be remarked are the forecast winds, temperatures, amount and value of the payload and the operational constraints for the aircraft. All of them have an impact on the cost efficiency of each flight.

However, for the purpose of developing the flight plan program, the one that has the bigger influence, and at the same time that can be included into the algorithm, is the wind. This meteorological phenomena is one of the principal data that should be checked before initiating a flight, and also should be considered during its development.

3.2.1 Wind and its influence

The flight of an aircraft is highly affected by the influence of the wind. Depending on its blowing direction and intensity, the aircraft can either benefit or be harmed in its trajectory, so that the consideration of this meteorological phenomena within the algorithm becomes relevant.

In the cruise phase, the wind is normally measured by using the equation relating it to the true airspeed and ground speed of the aircraft. This relationship is normally known as triangle of velocities.

This triangle of velocities states that the ground velocity[4] of the aircraft will be equal to the sum of the true airspeed or TAS[5] of the aircraft plus the velocity induced by the wind, as can be seen in equation (3.1).

$$\vec{V_G} = \vec{V_{TAS}} + \vec{V_W} \tag{3.1}$$

Therefore, equation (3.1) can be used to calculate the intensity and direction of the wind, once the true airspeed and ground speed data are known. The ground speed is normally determined through inertial navigation systems or INS[6], while the true airspeed is calculated through pitot-static systems[7].

[4]The ground speed is the horizontal velocity of an aircraft relative to the ground.

[5]The true airspeed or TAS is the speed of the aircraft relative to the mass of air in which it is flying.

[6]Inertial navigation systems consist of a number of accelerometers and gyroscopes that measure all accelerations and rotations of the aircraft throughout the flight, and by mathematically integrating them, the navigation system is able to compute the speed and position of the aircraft at any time. However, its accuracy is limited. Other modern methods to calculate the ground speed are external radio signals (GPS, Distance Measuring Equipment or DME, etc.)

[7]The pitot-static systems work by measuring the difference between static pressure, determined thanks to one or more static ports, and stagnation pressure, captured through different pitot tubes. With these data, the TAS of an aircraft can be measured. Also, it can be measured through the use of GPS.

Regarding meteorological information near airports, the data about the wind is normally included within the METAR[8] and TAF[9] reports, accessible through the AIP provided by each country. This wind information is normally provided with respect to the geographic north, so that if the aircraft is following magnetic routes, the magnetic declination must be taken into account.

Therefore, knowing how the wind blows, the way in which it affects the flight can be determined. For this purpose, the blowing direction of the wind plays an important role, as the sum in equation (3.1) is vectorial. Thus, if the wind blows along the heading of the aircraft, that is, if it follows the same direction than the true airspeed, two different cases can occur:

- Headwind: The wind blows against the direction of travel, decreasing the ground speed of the aircraft. Therefore, $\vec{V_W}$ would have a negative sign.
- Tailwind: The wind blows in the direction of travel, increasing the ground speed of the aircraft. Thus, $\vec{V_W}$ would have a positive sign.

The resultant ground speed will logically have the same direction than both the true airspeed and the wind velocity.

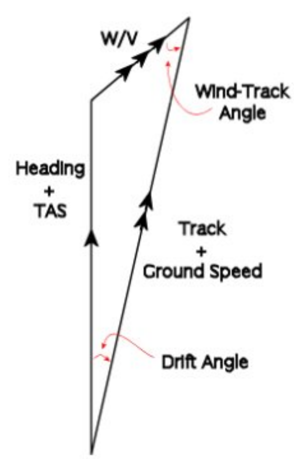


Figure 3.1: Triangle of velocities with a crosswind component. *Mathematical solution to the triangle of velocities, Steven Hale.* [6]

On the other side, if the blowing direction of the wind has some angle with respect to the heading of the aircraft, a headwind or tailwind component,

[8]METAR: Meteorological Aerodrome Report, international standard used to emit information about the meteorological conditions around all aerodromes, although they can also come from permanent weather observation stations. These information is normally communicated as part of the AIS.

[9]TAF: Terminal Aerodrome Forecasts, similar to METARs, they are forecasts of the meteorological conditions affecting a determined aerodrome. They are normally emitted every six hours, and they apply for a 24 hour period.

depending on the sense of the wind, appears parallel to the heading, and also a crosswind component is found perpendicularly to the true airspeed direction.

An example can be seen on Figure 3.1. In these cases, further unknowns play a role, like the drift angle and the wind-track angle, both observable in Figure 3.1, so that the direction of the wind and of the true airspeed shall be known to obtain both the magnitude and direction of the ground speed.

As it is logical, a strong crosswind component can deviate an aircraft from its desired track. In these cases, normally a calculation of the necessary correction, using equation (3.1) and graphic methods, is needed to describe the desired trajectory.

Influence on the optimum route

All these data serves to make an idea of how the wind can affect a flight on all its phases.

On its cruise phase, for example, the aircraft can take advantage of the blowing direction of the wind and acquire a higher velocity while consuming less fuel. On the other hand, if the aircraft encounters a zone with strong headwind or crosswind components, a higher fuel consumption would be needed to achieve an adequate velocity, and the necessity of making corrections would mean that the aircraft would spend more time and fuel.

This exposes the importance of the availability of weather forecast in any flight planning process, as with the help of the wind, an optimum route in terms of time can be found.

Another evidence that can be extracted from this line of thought is that not always the shortest route will be the same than the quickest route.

As it was seen in chapter 2, the flight planning tool finds the shortest route following the calculation of the great circle distance between each waypoint. Following this approach, it seems logical that if the shortest path is followed, the time spent will be minimum.

However, with a deeper thinking and taking into account the information seen in 3.2.1, it is possible to describe a quicker route using the influence of the wind, even if its longer in terms of distance.

To illustrate this idea, Figure 3.2 serves as a good example, as it can be observed that although the shortest route, or great circle distance, seems more direct, a wind optimal path can be followed, reducing in this case the flight time by a 2% and the fuel burnt by a 3%, while covering a distance 11% longer than using the great circle route, as seen in [7].

Concluding, the benefits of including the influence of the wind on the flight planning process are evident. Only by introducing the forecast wind to the model, which has already included the natural limitations imposed by air traffic management and control, the flight planning tool could be able to optimize the flight not only in terms of distance, but also in terms of time.

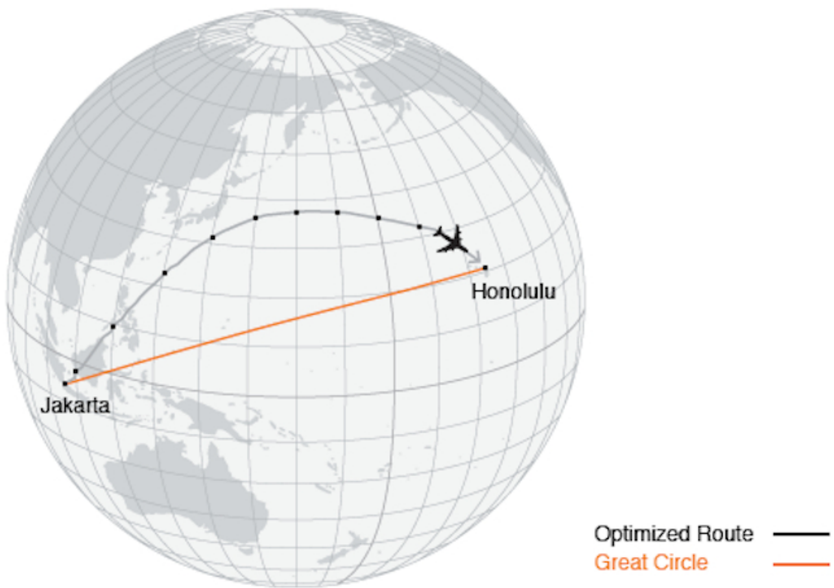


Figure 3.2: Flight from Jakarta to Honolulu showing the shortest or great circle route and the wind optimal route. *Effective flight plans can help airlines economize, AERO Magazine.* [7]

3.3 Adapting the wind to the model

Including the possibility of offering to the user to optimize its flight plan either in terms of distance or in terms of time seems to compose a pretty consistent flight planning tool.

Once the first option has been already developed and implemented, the model used for that purpose has to be re-adapted to include the wind influence on the algorithm. But first, it is necessary to find and define the way in which the wind information is provided.

3.3.1 Acquiring the wind information

The objective is to find the wind forecast information in an electronic format that could be integrated into the already known model, so that the algorithm can include them into the computations.

For this purpose, different sources can be consulted. One of the most renowned services related to meteorological information is the TIGGE Data Retrieval (see [23]) server from ECMWF[10]. This service allows to any public user

[10]ECMWF: European Centre for Medium-range Weather Forecasts: independent intergovernmental organization famous for providing the most accurate weather forecasts across Europe.

the possibility of downloading a series of datasets regarding weather forecasts across all the European territory.

The information included in these datasets can be filtered in its downloading. Therefore, the forecasts for specific days, timespan, office of origin[11], and, which is most relevant, for particular data, can be selected. This means that it allows to download specific wind information, more particularly, the wind components in two predetermined directions (north-south and east-west components). These data is defined in arbitrary points through the European airspace defined by its geographical coordinates, as can be seen in Figure 3.3.

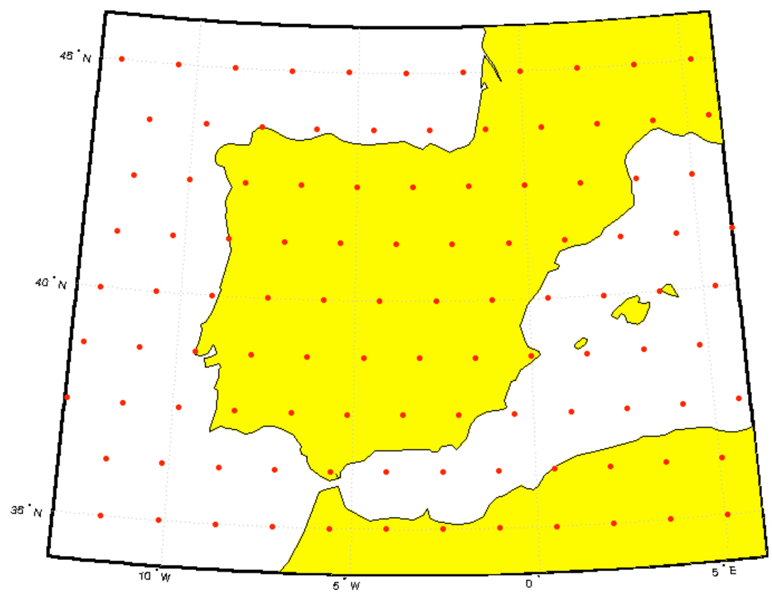


Figure 3.3: Network of points where the wind information is defined over the Iberian Peninsula airspace

Another relevant source is a server that can be accessed through the National Oceanic and Atmospheric Administration[12] (NOAA). The service provided through its File Transfer Protocol (FTP) Site (see [24]) allows also the downloading of specific wind information in a similar format that the one provided by ECMWF.

In this case, the information is slightly more complete because the wind data is provided for different altitudes, allowing to define it in the algorithm at the

[11]The information gathered in the TIGGE Data Retrieval service comes from the weather forecast data collected by different meteorological offices: Météo France, UK Met Office, National Centers for Environmental Prediction (NCEP), Bureau of Meteorology, ECMWF and many more.

[12]The National Oceanic and Atmospheric Administration is the American agency in charge of studying the conditions of the oceans and the atmosphere.

cruise phase altitude. This information is also defined for a grid of points like the one that can be observed in Figure 3.3.

A feature in common that all the datasets downloaded from both sources have is that the format of the files is GRIB (Gridded Binary or General Regularly-distributed Information in Binary form). This specific format is the most commonly used when distributing and storing historical and forecast weather data, as it was standardized by the World Meteorological Organization (WMO).

The problem with this data format is that it is not readable by a common programming tool, so it must be translated to a readable format (commonly, text formats) through the use of the GRIB-API[13] tool (see [25]).

Once the information contained in the GRIB files is accessible and readable, it was filtered for the areas of interest for this work, as the files contain information for the whole world.

With this, the necessary data for integrating the wind into the algorithm was acquired, so now it is required to adapt the model to make it calculate the quickest route with the consideration of the wind influence.

3.3.2 Incorporating the wind information

Recalling what was seen in section 2.3, the base of the program is the application of a Dijkstra's algorithm over a network of waypoints, where the path will be found by the analysis of the weights established for the connections between each node. Then, the adaptation of the wind data to this model could be directed to define the weights of the segments as a function of the wind influence.

However, the objective is to optimize the flight plan with respect to time, and the wind information available consists on direction and velocity components. Hence, a way of relating all the possibilities should be found.

In fact, a simple relationship can be established between all the data available, as the distance between each segment is known thanks to the development carried out in section 2.3.1. Then, if a cruise velocity is established for the whole flight (recalling the assumptions made in section 1.6, only the cruise phase is under consideration in this work), the time that the aircraft needs to cover an specific segment can be obtained. Furthermore, if the way in which the wind is affecting the aircraft could be known, the velocity contribution of the wind can be added or subtracted to the cruise velocity of the aircraft, and hence, the wind influence would be integrated into the model and the optimization in time could be carried out.

This opens a new possibility of customizing the flight plan optimization for the user, as the type of aircraft now will play an important role: depending on the aircraft used, and what's more, depending on the desired cruise velocity (which in turn is dependent on the amount of payload, cargo, operational and scheduling constraints, etc), the optimization in time will provide different outputs.

[13]GRIB-API: Grib Application Programming Interface, used for encoding and decoding WMO FM92 GRIB data written in edition 1 and edition 2 formats.

The way in which all these steps are going to be executed has to be checked deeper, as there are some assumptions and variables that require a more detailed definition.

Calculation of the wind influence

As it can be seen in Figure 3.3, the information available is a grid of arbitrary points over the whole European airspace where the components of the wind in the north-south and the east-west directions are defined. When filtering the data of interest, it is important to set a cruise altitude for the grid of *wind points*[14], as the cruise phase is the one under consideration. For this work, it has been decided to use the wind information at FL360.

For the purpose of adapting this information to the network of waypoints, a region of influence must be defined within each wind point. This determined region will filter the waypoints that suffer the influence of the wind defined for each wind point. Further on, it will be seen how to quantify this influence, but establishing this region allows a previous filtering that will improve the efficiency of the next calculations.

Specifying, the region of influence (with the form of a rectangle with curved sides) of each wind point embraces all the waypoints in the proximity of 0.75º of latitude and/or 1º of longitude, which, easing the understanding, defines an equivalent zone of influence of around 40-50 nautical miles of radius. The establishment of these specific numbers is done taking into account the density of wind points and the number of waypoints under consideration, basically in order to execute efficient calculations.

Once the waypoints that will be under the influence of wind corrections are known, now it is important to see how this wind is affecting each waypoint. For doing so, it is necessary to quantify this influence in the two components where the wind is defined for each waypoint, which is going to be carried out using an inverse distance weighted interpolation.

An individual region of influence of a single wind point would be similar to the situation reflected in Figure 3.4, where five different waypoints are affected by the influence of a single wind point. Therefore, to know the actual wind components at each waypoint, the application of some kind of interpolation becomes evident.

Thus, as mentioned before, the inverse distance weighted interpolation (IDW) is used, which states that elements that are close to one another are more alike than those elements that are farther apart. This means that the IDW assigns a local influence to each wind point that diminishes with distance, so that for waypoints closer to the wind point location, a greater influence is going to be assumed. Once again, it will be required to calculate the distance between the wind point and each waypoint following the process already explained in section 2.3.1.

[14]The points at which the information about the wind is defined will be known as wind points further on in this work.

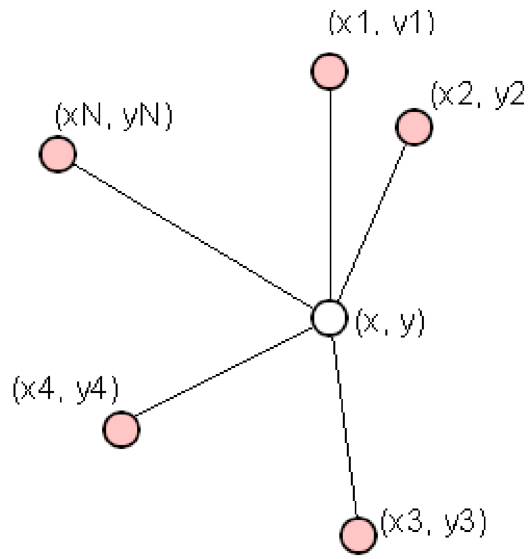


Figure 3.4: Simplified scheme of the region of influence of a wind point (white) over different waypoints (pink). *Class notes, chapter 29, Quantitative decisions.*

When every distance is known, the interpolation for calculating the wind components on each waypoint can be executed applying the following formula:

$$|Vw_{wayp}| = \frac{|Vw_{windp}|}{D^p} \tag{3.2}$$

where every element is defined as:

- $|Vw_{wayp}|$ is the calculated module of the wind velocity for both directions known at each waypoint.
- $|Vw_{windp}|$ is the module of the wind velocity in each direction for the considered wind point.
- D is the distance between the waypoint and the windpoint under consideration.
- p is the power value determining the rate at which the influence decays with the distance.

The power value used for the calculations in these cases should be selected carefully. In Figure 3.5, the way in which the influence evolves depending on the selection of the power value can be observed.

It is obvious that with $p = 0$, there is no decrease with distance, but as p increases, the influence for distant points decreases rapidly, and only the waypoints in the immediate surroundings will suffer a relevant influence.

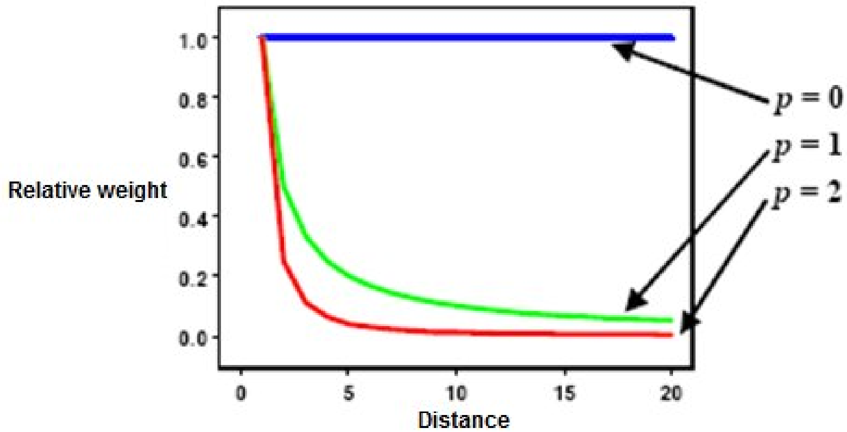


Figure 3.5: Evolution of the influence on distant points with different power values. *How inverse distance weighted interpolation works, ArcGIS Resource Center.* [8]

Knowing this, for these particular cases, a power value of 0.75 will be selected.

Normally, in geostatistical analysis, the power values used are close or greater than 1, but in these cases, due to the magnitudes of the wind velocities, where the maximum is about 40 knots, being relatively small compared with the distances under consideration (the maximum ones are close to 60 nautical miles), in order to have an actual appreciable influence, an smaller power value is chosen.

This model may not be perfectly adjusted to reality. In fact, the only data known is the wind at an specific point in two determined directions. As far as it is known, in a waypoint located only 5 nautical miles away from this point, the wind could be blowing in another direction with a very high or very low intensity compared to the known one.

However, with the application of this model, an uniformity in the wind behaviour in assumed, which in fact is a normal pattern in actual situations.

Furthermore, the advantages of using the inverse distance weighted interpolation can be directly observed, as it allows to calculate rapidly the components of the wind at each waypoint with a precise control on the relationship between real influence and distance.

The principal disadvantage of this kind of interpolation is that it is not possible to do a direction-dependent weighting, so that spatially oriented relationships can not be established. In any case, for this calculations is not really relevant to define a directed influence, as is in the following step when the direction of the wind components play an important role.

Projecting the wind components

With the calculation of the wind influence, it was established that each waypoint has two components of the wind with determined intensities and directions.

However, as it was exposed in section 3.3.2, for incorporating the wind to the model of the algorithm, it is necessary to obtain the contribution of the wind in each connection between waypoints.

Therefore, calculations should be made to project the components of the wind at each waypoint to the specific direction of each connection, so that the influence of the wind along the flight plan trajectory can be determined.

For this purpose, the only element needed is the actual direction of each connection. Only by calculating the angle that the connection draws with the two directions where the wind is defined for each waypoint (as mentioned before, north-south and east-west), the projection could be made effectively. Then, the posing of the problem can be simplified as to calculate the angle that the connection describes in a 2D plane with the x and y axes.

To carry out this calculation, the only information available is the geographical coordinates of the two waypoints defining the connection. Although with this the geographical distance of the segment joining them can be found, it is not enough to calculate the angle.

This is because longitude and latitude do not provide measurements of length, as they are simply references to the World Geodetic System 1984. This reference coordinate system, also known as WGS84, is the one used by Global Positioning Systems, and it basically models the Earth as an ellipsoid, whose center coincides with the Earth's center of mass.

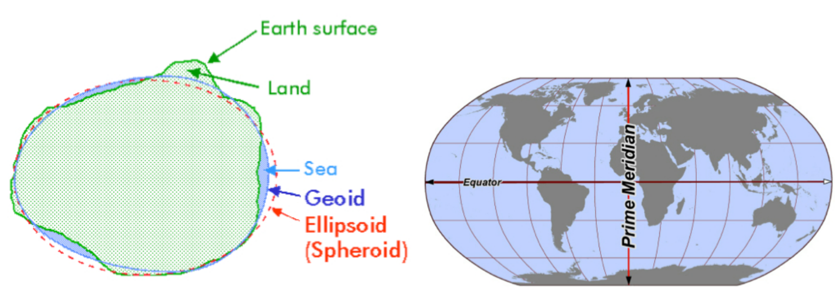


Figure 3.6: World Geodetic System 1984 Earth representation. *Department of Agricultural and Biological Engineering, University of Illinois.* [9]

Then, another way of representing the location of points over the surface of the Earth must be found to calculate an angle properly. It is concluded that the best way to represent the data would be in a Cartesian plane, where points will be given by two coordinates (x,y) in units of length.

Therefore, a calculation should be made to convert the available geographical coordinates in degrees to a coordinate system based on lengths. In order to do it, the first assumption that should be made is to model the ellipsoidal datum of the WGS84 as a sphere, so that the Earth can be considered to have a constant radius.

A datum should be chosen for the new system of Cartesian coordinates. In order to keep all the values in the positive range to ease the calculations, the datum will be constituted by the minimum values of longitude and latitude available. With the system of coordinates properly defined, now the only thing left is to establish a formula to fit the points defined through geographical coordinates into the Cartesian plane. Thus, to reference the latitude from datum, the following formula can be used:

$$Y = (L_n - L_{min}) \cdot (R \cdot \frac{\pi}{180}) \tag{3.3}$$

where each element is defined as:

- Y is the desired y-coordinate of the waypoint under consideration.
- L_n is the latitude of the waypoint under consideration, while L_{min} is the minimum latitude considered.
- R is the radius of the Earth (6371 kilometre)

And the longitude can also be converted using the following formula:

$$X = (L'_n - L'_{min}) \cdot (\frac{\pi}{180} \cdot R \cdot cos(L_n \cdot \frac{\pi}{180})) \tag{3.4}$$

which in this case is constituted by the elements:

- X is the desired x-coordinate of the waypoint under consideration.
- L'_n is the longitude of the waypoint under consideration, while L'_{min} is the minimum longitude considered.
- L_n is the latitude of the waypoint under consideration

With both formulas (3.3) and (3.4), the network of waypoints is referenced into a Cartesian plane, hence, the angle between each connection can be calculated straightforward through the application of basic trigonometry.

Thus, the projection of the north-south and east-west wind components can be effectively carried out for each specific connection. The output coming from these projections is the contribution of the wind in two different directions: along and perpendicular to the flight path track. With respect to the former, it is important to clearly define its sign, as having headwind supposes a negative contribution, while having tailwind, a positive one.

With respect to the crosswind contribution, it will not be included into the algorithm. This is because the wind blowing perpendicular to the plane heading does not have an immediate effect on the aircraft's velocity. Obviously, a strong crosswind deviates the aircraft from its optimal track, and therefore supposes an additional time lost in direction deviations and corrections, which in most cases is very small.

However, due to the difficulty in determining at which wind intensity the aircraft would start deviating and in calculating the actual time lost, the neglect of the crosswind component becomes a feasible assumption.

3.3.3 Completing the model

Once the wind is fully adapted to the algorithm's model, the only thing left is to change the output of the algorithm in order to make it dependent on the time. As it was commented before, this was possible through the combination of a establishment of a predetermined cruise velocity (TAS) with the already known lengths of each connection.

The selection of the aircraft's velocity depend on different factors, as the amount of payload and cargo on board, the operational ans scheduling constraints of the specific flight, the type of aircraft, regulations coming from air traffic control, and more. Therefore, two different options can be offered with respect to the establishment of the aircraft's true airspeed:

- Assign automatically a predetermined cruise speed depending on the type of aircraft introduced as input by the user.
- Allow the user to introduce a desired cruise speed, which could be different than the predetermined one, depending on all the variables under consideration.

Both alternatives will be offered in the flight planning tool. For the first one, and as example, two types of aircraft that will be introduced in the program are the Airbus A320 and the Boeing 737, which will serve to illustrate which data is needed to complete the model.

Type of aircraft	Mach at cruise altitude	Cruise speed (TAS) [kts]
Airbus A320	0.78	447
Boeing B737	0.74	421

Table 3.1: Values introduced in the algorithm to complete the model.

Then, to the cruise velocity introduced by the user, the value of the contribution of the wind should be added or subtracted for each specific connection, following the information stated in section 3.2.1. Consequently, the ground velocity of the aircraft along the flight path direction will be computed for each segment of the airways network.

Finally, to express the weight of each of these segments in terms of time for the algorithm, it is as easy as dividing the length of the segments, calculated previously on chapter 2, by the variable ground velocity of the aircraft. With this, the time that the aircraft takes to travel from waypoint to waypoint is effectively calculated.

A simple example with the information that will be used for the next section can be exposed to see the final data structure. The segment MAZET-AVN can be covered with a Boeing 737 (taking the data from Table 3.1) in 2.42 minutes without any wind influence, as it has to travel 17 nautical miles.

However, taking into account a small wind component of 9.39 knots in headwind configuration (extracted from the real data included in the algorithm), the ground speed of the aircraft would be reduced to 411.61 knots, and then the segment will be covered in 2.478 minutes, an increase of 2.4% with respect to time. This does not seem a relevant variation, but taking into account that there are higher wind components and that a flight route is composed of many segments like this, the total variation can end up having an important influence on the results.

3.4 Test cases

Now, it is important to check if the algorithm is still capable of providing logical outputs to each posed flight plan, and also that it completes all the calculation processes in a relatively small time.

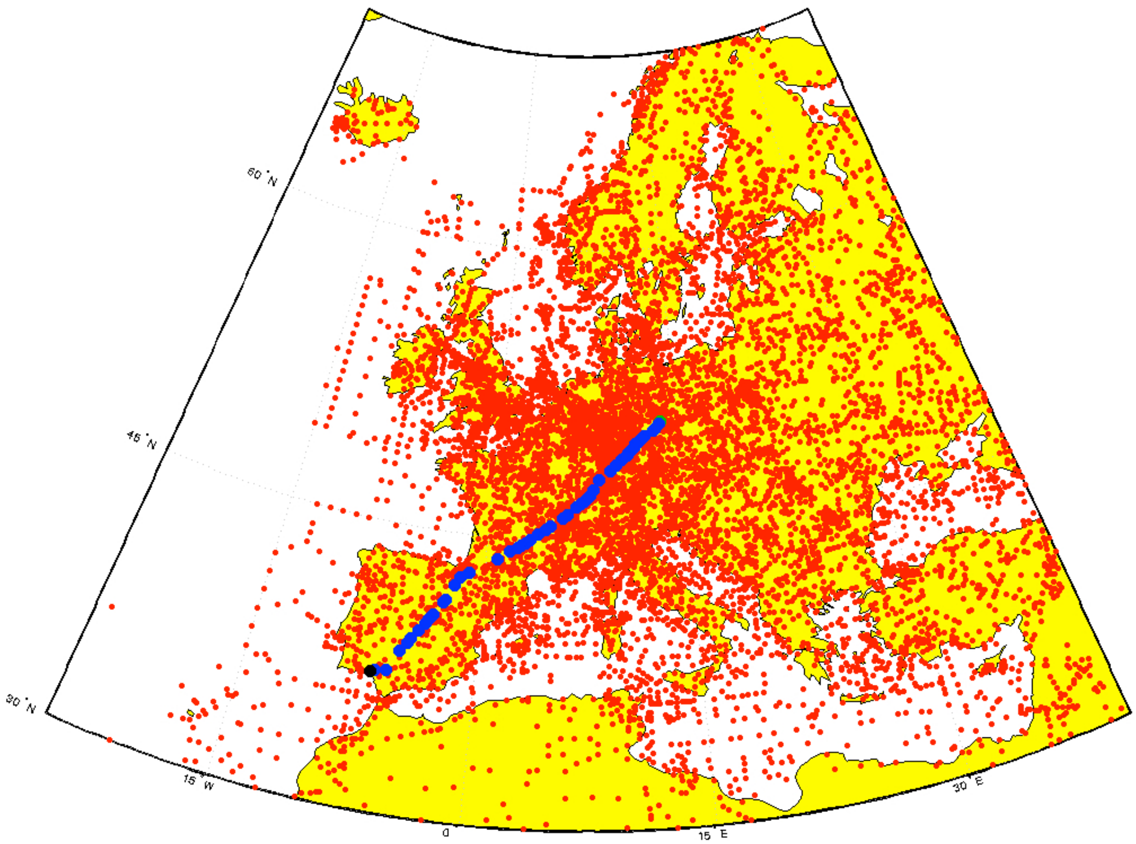
As it has been explained before, now the customization of the flight plan acquires a new level with the necessity of inputing either the type of aircraft used or the desired cruise velocity. This adds a certain value to the program, as it brings it closer to actual flight planning tools being used nowadays.

For checking the correct performance of the algorithm, a simple case across Europe will be computed. In this case, the origin will be located in the VOR of Dresden, Germany (*DRN*) and the destination will be again in Spain, this time on the waypoint *ONUBA*. The aircraft selected will be the Airbus A320, whose cruise velocity can be observed in Table 3.1. The data about the wind used corresponds to the 14^{th} July 2015.

As it can be seen in Figure 3.7, the output seems to provide logical results. With respect to the computation time, the information of the path is obtained in approximately 6-7 seconds, while the graphical representation is provided in 10 seconds. This supposes an increment of about 2 seconds with respect to the computational times for the calculation of the shortest distance without the influence of the wind.

However, this increment was expected to occur due to the handling of a bigger set of data, which complicates the calculation of the optimum route. In any case, it can still be considered an acceptable computational time taking into account that it is a medium range flight that crosses the zones of the European airspace with a higher connections density.

For this case, it can be seen that the algorithm provides the distance that the aircraft covers together with the flight time. Theoretically, the optimized value is the one for the flight time, meaning that the path shown is the one that represents the quickest route connecting the desired origin and destination, and not the shortest route. Then, there could exist a different flight route that would complete the flight covering less nautical miles, but in a higher time.




```
Path =

    'DRN'
    'BESIP'
    'ABKIS'
    'NOKSI'
    'PEROX'
    'NURGO'
    'URONA'
    'UNAVI'
    'KULOK'
    'ERETO'
    'ANELA'
    'KEGOS'
    'AMOSA'
    'ODEGU'
    'DKB'
    'GUPIN'
    'TEDGO'
    'NATOR'
    'RINLI'
    'OLBEN'
    'LUTIX'
    'BENOT'
    'NEMOS'
    'VEROX'
    'MILPA'
    'NINTU'
    'MEBAK'
    'REPSI'
    'LERGA'
    'MOKDI'
    'OLRAK'
    'ROMAK'
    'NASEP'
    'NARAK'
    'AGN'
    'PIPOR'
    'PPN'
    'VASUM'
    'HERMI'
    'BANVO'
    'MITUM'
    'BOSIO'
    'GOTOR'
    'KAMPO'
    'MONTO'
    'MOLIN'
    'HIJ'
    'SVL'
    'PIMUR'
    'ONUBA'

Time: 164.90 minutes.
Distance: 1227 nautical miles.
```

Figure 3.7: Flight plan information for route *DRN-ONUBA* with an Airbus A320.

The logical thought is to suppose that the shortest route should also be the quickest one, but as it has been seen throughout this whole chapter, the influence of the wind can make a difference, so that it provokes that the quickest route is not the same than the shortest one.

The best way to appreciate this influence of the wind is to introduce a flight plan where this difference is visible. This is the case of the flight route connecting the waypoints *KOSMO* and *CARBO*, for which both the shortest and the quickest route technical information is shown in Figure 3.8. This time the aircraft used for the calculations is a Boeing 737, and the wind information corresponds again to the one for the 14^{th} July 2015.

```
Distance: 1382 nautical miles.
```

(a) Shortest route information

```
Time: 196.80 minutes.
Distance: 1384 nautical miles.
```

(b) Actual quickest route information

Figure 3.8: Flight plans technical information for route *KOSMO-CARBO*.

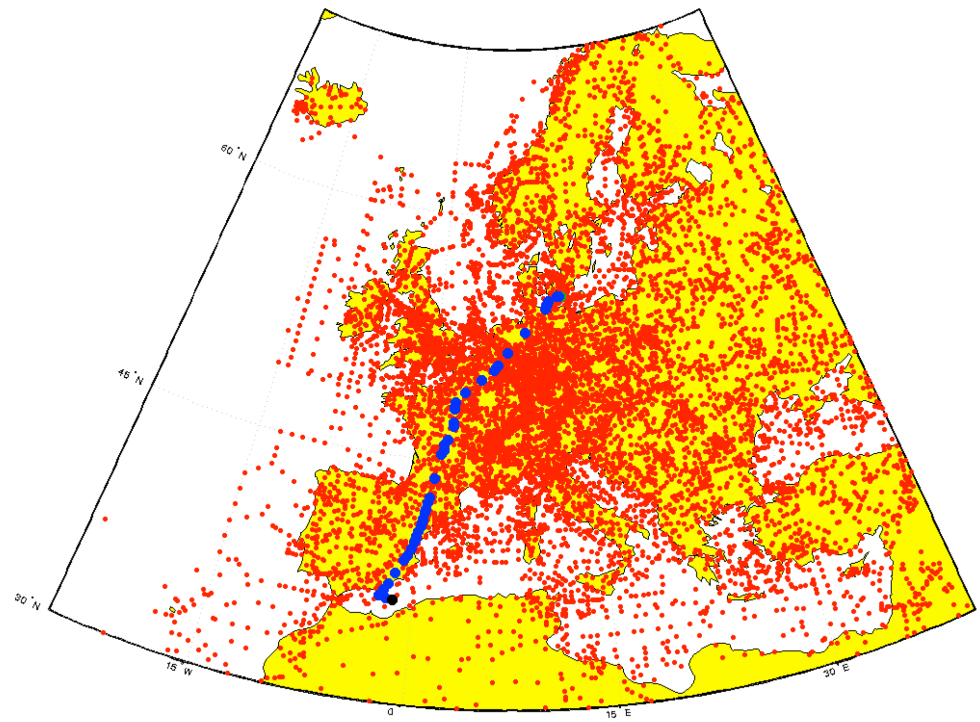
In this case, the sequence of waypoints of each route is not shown, as the graphical representation shown in Figure 3.9 will serve to expose the differences between them. Figure 3.8 helps in showing that the distance covered when following the quickest route that the wind allows to find is higher than the ideal shortest one. In this particular case, the variation in length is not that big, but in Figure 3.9, it can be seen that the difference lies in the path to be followed.

The time needed to cover the shortest route under the influence of the wind is not provided by the algorithm. When using the flight planning tool, the user should decide between optimising their flight plan in terms of distance or in terms of time. For the latter case, the quickest route is the one shown to the user, thus, the time needed for any other route, including the time for the shortest route, will be higher, and consequently, not interesting for the user.

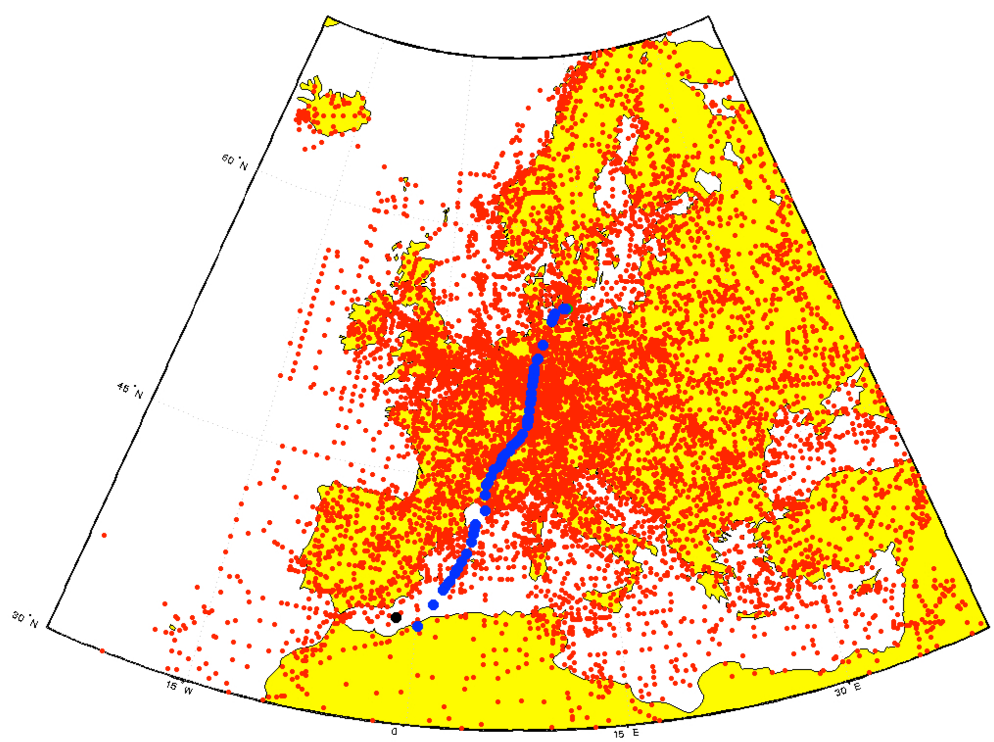
Conclusions

As it can be seen in Figure 3.9, the path to be followed depending on the type of optimization selected by the user is completely different. This exposes the relevance of the influence of the wind in the flight planning process, as is the feature that marks the selection of one route or another.

In addition, this confirms that the performance of the algorithm is optimal, and globally, it can be considered that the flight planning tool is consistent. The inclusion of the possibility of optimizing the flight plan in different terms, together with the further personalized inputs, enhances the usage experience of the program.



(a) Shortest flight plan for the route *KOSMO-CARBO*, correspondent to data in Figure 3.8a.



(b) Quickest flight plan for the route *KOSMO-CARBO*, correspondent to data in Figure 3.8b.

Figure 3.9: Flight plan representations for route *KOSMO-CARBO*.

Chapter 4

Implementing schedules

Until this point, the model proposed is capable of optimizing a flight plan in terms of distance and time based on the network of airways defined for the whole European airspace. This network is constituted by a set of waypoints that serves as milepoints along the air defining the airways that should be followed by aircraft.

However, a variable that has not been included yet in the algorithm is the availability of these airways. Through the establishment of the airways network in the first steps, only the natural limitations based on the definition of connections made were included. It has been seen that these connections definitions change with every AIRAC cycle, and that a manual upgrade of the information must be made to keep the algorithm updated.

Despite of this, as it has also been previously said in section 1.5, there are further limitations applying in the European airspace. Therefore, the inclusion of these restrictions into the model becomes now a necessary feature, so that the algorithm can offer actual solutions adapted to real situations.

4.1 Restricting the airspace

Not all airway segments are available at all times and to all aircraft. The application of restrictions is constant throughout a normal operation day, and in spite of this, the present structure of the airspace is capable of withstanding numerous limitations without stopping to provide efficient communications.

These limitations have its origin in different sources, and it is interesting to know some of them to understand better the reasons that lie behind the necessity of applying them.

Restrictions in the airspace can be established in different phases of the flight planning process. For the strategic term, the one that holds months and weeks before an actual flight plan is needed, numerous factors influencing the availability of the airspace are defined.

A relevant factor amongst these, that normally holds for long times, is the definition of determined zones of the airspace where the aeronautical authorities of each country consider that no aircraft should overflight. Usually, restrictions applying in these zones respond to issues related to national security or with the interference with populated or ecological areas. Also, the use of the airspace by military aviation imposes further restrictions on specific zones. There are different types of limitations depending on the area definition:

- Prohibited Zones: Airspace of defined dimensions inside of which commercial flights are not allowed.
- Restricted Zones: Zones whose use is under authorisation, complying with very specific conditions.
- Dangerous Zones: Areas where activities which can be dangerous for aircraft take place, following an established and limited schedule.
- Temporarily Segregated Areas: Its availability requires an airspace reservation for the exclusive use of specific users during a predetermined period.

As it can be seen, the availability of these restricted zones depends on a very specific schedule which is tightly established in the strategic term, and more particularly, through the AIP of each country, and is normally revised in the Appendix 2 of the Route Availability Document (see [12]).

In the aforementioned Route Availability Document, which, as was explained in section 1.5, is updated with every AIRAC cycle, further information about the establishment of limitations in the strategic term can be encountered. Most of them can be found on its appendices, as can be the applying DCTs[1] Map in Appendix 4 (see [26]), the Flight Profile restrictions in Appendix 6 or the FUA restrictions in Appendix 7.

The AIP also contains the definition of the conditional or CDR routes, which, as can be seen in [27], are routes that are only available for flight planning and use under specified conditions. These definitions go from the strategical to the tactical term, depending on the specific category of the CDR under consideration:

- Category One (CDR1) - Permanently plannable: CDR1 routes are available for flight planning during the times published in the correspondent AIP. Thus, they are available most of the time, and when not, because of punctual situations (for example, due to the temporal activation of a military training zone).

[1] DCT: Waypoint-to-waypoint routing which does not use any airway. They are exceptionally used when a suitable airway is not found, or when the usable airways suppose a roundabout route.

- Category Two (CDR2) - Non-permanently plannable: They may be available for flight planning under specific conditions, such as facilitating traffic flow and increasing ATC capacity. For a flight to be planned on a CDR2, it must be in accordance with the conditions published daily in the CRAM[2].

- Category Three (CDR3) - Non-plannable: They are not available for flight planning. They are only available on short notice (in the tactical term), following ATC instructions.

As it can be seen, the flight planning process is highly influenced by the restrictions imposed through the CDRs from the strategic term to the very tactical term.

With respect to the latter, further limitations can arise when the flight is under execution. Although this actually does not enter into the flight planning process, as the regulations that are imposed at the time of flight can not be predicted, it should be borne in mind that they can suppose a modification in the flight route described.

Events like adverse meteorological conditions, capacity limitations on airports, congestions on determined zones, ATC issues like staffing and human capacity provoke punctual unpredictable regulations which affect the execution of the pre-established flight plan.

Therefore, all the regulations stated above limit the use of the European airspace by establishing schedules in the availability of each airway or segment of airway, depending on each daily situation.

4.2 Scheduling the model

The inclusion of all the different regulations commented before into the algorithm would suppose an important quality upgrade to the model. If the output of the algorithm would be dependent on the applying regulations at the actual flight time desired by the user, the solution proposed, following the ATFM circuit, would accomplish the necessary standards for its actual consideration.

Consequently, this would ease the flight planning process for the user, as it would only need to introduce the desired input being sure that the flight route proposed will comply with the applying regulations and restrictions in the strategic and pretactical terms.

For this purpose, all the regulations exposed on section 4.1 should be integrated into the model. However, the principal problem with respect to them is that they are not available in a suitable electronic format, so the information can not be accessed easily. For example, all the regulations framed in the Route Availability Document can be observed in a PDF format (see [12]).

[2]CRAM: Conditional Route Availability Message. Daily airspace management message which promulgates the decisions on Conditional Routes availability notified by the Airspace Use Plan. They are published daily by the Eurocontrol Central Flow Management Unit.

This format allows the user to get to know the nature of these limitations, but prevents to extract that information in order to include it into the algorithm, as the only possible way to obtain all the data would be transcribing one by one all the regulations (totally inefficient due to the amount of regulations and to the fact that it should be done with every AIRAC cycle).

AIRWAY	FROM	TO	Point or Airspace	Utilization
UQ58	GIKIN	LAT		Only available for traffic ARR LICB/CC/CZ

Restriction Applicability	ID Number	Operational Goal
06:00 - 21:00 (05:00 - 21:00)	LI2238	To segregate traffic from the PEMAR traffic flow

Figure 4.1: Example of a typical restriction established in the RAD. *Extracted from RAD 1510 Checklist, EUROCONTROL.*

It is seen that the flight planning tools under current use by actual airlines access this information thanks to economical agreements with EUROCONTROL, so that they are provided with the necessary data in a suitable format.

This problem arises with every type of regulation seen in section 4.1, so that the possibility of including up-to-date aeronautical information regarding regulations becomes very complicated in this step of the development of the algorithm.

However, an action should be taken with respect to this matter, because optimizing the flight plan as a function of the flight time is a very interesting feature of a flight planning tool for any user. Therefore, although actual information can not be accessed, it would be important to develop the algorithm in such a way that it would be prepared to work correctly when real data about regulations becomes available.

The nature of the application of these regulations is known: they basically impose a schedule on the usage of every airway or segment of airway, making it not available for air navigation during a determined time.

Consequently, it was decided that a good way to adapt the model to include these regulations would be to create a schedule for each specific airway or segment of airway, imitating the schedules imposed by actual regulations, which would limit their availability for flight planning purposes. With this, an opening and closing time will be set for every connection, and outside that defined timespan, their use will not be allowed.

The opening times are randomly chosen following a uniform distribution between 00.00 and 12.00, and the closing times are selected with the same procedure, but between 13.00 and 24.00 (or 00.00 of the next day). These times are defined in intervals of one hour.

These fictitious schedules will be randomly established apart from the algorithm, and the idea is that they will be maintained for every AIRAC cycle, independently of which particular day is chosen.

4.2.1 Iterating to optimize

The functioning of the algorithm should now be redefined to account for the schedule of each connection. The first thing that should be implemented to start the process would be the input of the starting time of the flight, which should be introduced by the user.

This is a delicate matter, as it is very difficult for airlines to provide with accuracy the time at which the flight will actually start.

Normally, the take-off time for each flight is framed in a time interval of some minutes, which is usually determined by the air traffic flow authorities (CFMU[3]) and the air traffic control of each airport, and this particular take-off hour will determine the timing of the flight. In any case, an approximate starting hour can be provided for flight planning purposes.

It is important to be aware that for this flight planning tool, the aforementioned starting hour is actually the time at which the flight will start its cruise phase, and not the take-off hour.

Now, knowing the hour at which the flight will start its cruise phase, it will be necessary to introduce further calculations in each node composing the airways network.

Basically, the algorithm should determine the time at which the aircraft will arrive at each waypoint, and compare this time with the schedule of the next connection to see which one can be followed.

To understand this process better, each step should be detailed. Consisting the input introduced by the user on the origin and destination waypoint, together with the starting hour, it is clear that the schedule of each usable connection will determine the optimum flight plan.

The functioning will be the following: the algorithm will optimize the desired flight route, either in terms of distance or in terms of time (as the user desires), as it was explained in chapters 2 and 3. Then, from this, an optimum flight plan will be obtained as output.

Together with this, the time that the aircraft takes to complete each connection of the optimum flight plan is already known. In chapter 3, it was explained how to calculate the time needed to cover each airway or segment of airway under the influence of the wind.

Using this, each duration of the travel from waypoint to waypoint will be summed to the starting flight time (introduced by the user), so that it will be straightforward to know the particular time at which the aircraft arrives to each waypoint composing the optimum flight route.

Then, this will be checked against the fictitious schedules created beforehand. This process is done for every waypoint constituting the proposed flight plan, so that an iteration for each connection is needed. Thus, three options can apply for each iteration between two waypoints A and B:

[3]CFMU: Central Flow Management Unit, is the traffic management central unit of EUROCONTROL. Each flight plan across Europe is sent to the CFMU, and it is the responsible agent in charge of their approval or redefinition. Its principal objectives are to avoid traffic congestions and to maximize the airspace utilisation.

1. The aircraft arrives at waypoint A when the segment A-B is open, and the segment is still open when the aircraft arrives at waypoint B.
2. The aircraft arrives at waypoint A when the segment A-B is open, but the segment is closed when the aircraft arrives at waypoint B.
3. The aircraft arrives at waypoint A when the segment A-B is closed.

The first option is the less problematic one: the aircraft is still in time to comply with the schedule, so the segment could be followed and the flight route would not have to be changed.

The second option presents a conflict: the aircraft complies with the schedule when starting but not when finishing the connection, meaning that it uses a closed connection during a determined time. In this case, it has been decided that such happening is not allowable, so that if the algorithm detects that this occurs, the segment A-B could not be used and the flight route proposed should be modified.

A similar behaviour is followed when the third option applies: when a segment is closed at the time of arrival to the starting point, its use is obviously not allowed, and alternatives should be proposed.

In Figure 4.2, an example of a restriction limiting a proposed flight plan can be observed. As commented before, it can be seen that the complete flight route is proposed independently of the restrictions, and then its validity is checked against the corresponding schedules.

```
Path =

     'RATAS'   6.00
     'NEA'     6.04
     'ODAPA'   6.09
     'ORBIS'   6.10
     'DISKO'   6.12
     'KALMA'   6.17
     'TLD'
     'MONTO'
     'MOLIN'
     'HIJ'
     'SVL'
     'PIMUR'
     'ONUBA'

Restriction applied at sector KALMA - TLD

The sector is closed at the flight time span 6.17 - 6.21
```

Figure 4.2: Restriction applying to a flight plan proposed for route *RATAS-ONUBA* starting at 06.00 AM

Therefore, the algorithm will act depending on the option applying in each specific segment. If the first option applies, the connection is considered valid, and the algorithm will keep assessing the validity of the following segments.

On the other hand, if the second or the third option apply at any segment of the optimum flight route proposed, the validity assessment is stopped and a second iteration is produced in the algorithm: the problematic connection and the proposed flight plan are discarded, and the program will calculate the following optimum route without taking into account the discarded connection.

This second proposed flight route will have to undergo again the first iteration to check if it complies with the applying limitations, and then, the whole process will be repeated until a flight plan complying with the schedules is found.

Consequently, this process is expected to increase noticeably the computational time of the algorithm, as depending on the route and on the flight time introduced, the number of iterations needed to find a valid flight plan can be significant.

4.3 Test case

The correct performance of the algorithm with this new feature should be checked. As it was done with previous improvements, the possibility of including restrictions in the optimization is offered independently. Thus, the user can choose between optimizing with respect to time or distance with or without restrictions.

This time, the model is going to be limited to the Iberian Peninsula airspace, and not to the whole European airspace. This is to reduce the size of the output and to ease the checking of the functioning of the algorithm.

First, the whole iteration process of computing and discarding flight plans should be assessed, as it is the one that will determine the final output of the algorithm with restrictions. For doing so, it has been decided to show the iterations for the flight route *NEXAS-ZANKO*, which supposes a relatively short flight.

To compare against the non-restricted case, the same flight is shown in Figure 4.3 optimized with respect to time without restrictions in the airspace. Here, the optimum flight path regarding flight time can be observed.

Then, the different iterations for the same flight but with restrictions are shown in Figures 4.4 and 4.5. The aircraft used is an Airbus A320, and the starting flight time will be 08.50, which should be slightly problematic. This particular time is chosen to ensure that it will be possible to check that the algorithm makes properly the change of minutes from hour to hour.

It should be taken into account when observing the following examples that the restrictions introduced are considerably more limiting than the actual ones applying. In this model, the opening and closing times of each connection are established randomly following an uniform distribution, which is a conservative approach that does not imitate the reality with accuracy. Actually, it is very common that many airways remain open for the whole day, and just a minority are actually limited by schedule.

```
Path =

    'NEXAS'
    'ADUXO'
    'CJN'
    'LIPOR'
    'MITUM'
    'VEMAK'
    'MAGIN'
    'INDEG'
    'DISKO'
    'ZANKO'

Time: 28.00 minutes.
Distance: 209 nautical miles.
```

Figure 4.3: Optimum flight path with respect to time without restrictions for flight route *NEXAS-ZANKO* (Airbus A320 used).

```
Path =

    'NEXAS'  8.50
    'ADUXO'  8.58
    'CJN'    9.02
    'LIPOR'  9.04
    'MITUM'  9.06
    'VEMAK'
    'MAGIN'
    'INDEG'
    'DISKO'
    'ZANKO'
 Restriction applied to connection MITUM - VEMAK.
 Connection closed at flight time span 9.06 - 9.07
```

(a) First iteration

```
Path =

    'NEXAS'  8.50
    'ADUXO'  8.58
    'CJN'    9.02
    'PALIO'  9.05
    'AKOKI'  9.06
    'VISON'  9.08
    'BOSIO'  9.09
    'MAGIN'  9.13
    'INDEG'
    'DISKO'
    'ZANKO'

Restriction applied to connection MAGIN - INDEG.
Connection closed at flight time span 9.13 - 9.14
```

(b) Second iteration

Figure 4.4: First two iterations for the computation of the restricted flight plan for route *NEXAS-ZANKO*.

```
Path =

    'NEXAS'  8.50
    'ADUXO'  8.58
    'CJN'    9.02
    'LIPOR'  9.04
    'MITUM'  9.06
    'RBO'
    'NATUL'
    'OSTIX'
    'GASMO'
    'DGO'
    'NEA'
    'ZANKO'
Restriction applied to connection MITUM - RBO.
Connection closed at flight time span 9.06 - 9.08
```

(a) Third iteration

```
Path =

    'NEXAS'  8.50
    'ADUXO'  8.58
    'CJN'    9.02
    'BRITO'
    'LARDA'
    'RONKO'
    'TURPU'
    'PPN'
    'MIRPO'
    'DGO'
    'NEA'
    'ZANKO'
Restriction applied to connection CJN - BRITO.
Connection closed at flight time span 9.02 - 9.08
```

(b) Fourth iteration

```
Path =

    'NEXAS'  8.50
    'ADUXO'  8.58
    'CJN'    9.02
    'PALIO'  9.05
    'AKOKI'  9.06
    'VISON'  9.08
    'GOTOR'  9.09
    'TLD'    9.13
    'MELON'  9.19
    'ZORBA'  9.23
    'ZMR'    9.34
    'ORBIS'  9.43
    'DISKO'  9.45
    'ZANKO'  9.50
```

(c) Fifth iteration

Figure 4.5: Three last iterations for the computation of the restricted flight plan for route *NEXAS-ZANKO*.

Different conclusions can be extracted from the results obtained in Figures 4.4 and 4.5.

Comparing both paths from Figures 4.3 and 4.4a, it can be seen that they are the same. This is because, as was stated in section 4.2.1, the first flight plan proposed in the iterative process should be the optimum one obtained from the optimization without restrictions, so that in this aspect, the algorithm behaviour is the proper one.

Then, it can be seen in all the iterations that the algorithm tries with different optimum paths until eventually one does not encounter any applying restriction in its way. It is interesting to see how for the path proposed in the second iteration (Figure 4.4b), no restriction is found until almost the end, and then, in the third iteration (Figure 4.5a), the path is different and is discarded way before than the previous one. This means that the algorithm does not take almost successful paths that has been discarded into account for future calculations, instead, it keeps proposing the next optimum flight plan, even if it is completely different than the ones proposed before. This is the expected conduct, as the objective is to offer the optimum route in any case.

This also means that as the number of iterations to obtain a valid result is increased, the efficiency of the optimization decreases. This is because for each iteration that fails to encounter a valid flight plan, the effective optimum route for each case is discarded, so that the next proposed solution will be worse in terms of optimization.

Another observation that can be made is that the times are computed correctly, so that the change of minutes and hours is carried out properly.

With respect to the final results, as expected, it can be observed that the schedules proposed are very limiting, as for a flight which can be completed in 28 minutes (as can be seen in Figure 4.3), the proposed optimum flight plan with restrictions takes 1 hour to be completed. In a real situation, this difference would be significantly reduced, as the restrictions applying are not so limiting.

Also, an important variable that changes the output is the desired starting hour of the flight. For the distribution of opening and closing times, it is seen that in the mid hours of the day, the number of iterations is effectively decreased, while as the starting flight hour is shifted towards the first or the last hours of the day, the restrictions are increased and thus the proposed solution is less optimum. For the example proposed, whose actual optimum flight time is of 28 minutes, the different flight times and number of iterations obtained depending on the starting flight hour can be observed in Table 4.1.

However, as commented before, the way in which the schedules are established is arbitrary and very restrictive, so the results that are obtained do not fit the reality accurately. In any case, the application of these schedules helps in the development of the program, and eventually, they serve to show that the algorithm behaves perfectly in a very restricted environment. Therefore, once the data that represents properly the actual situation of the restrictions is available, the model will be prepared to compute the flight plans according to the real situation without any problem, as the airspace will be noticeably less limited.

Starting flight hour	Number of iterations	Duration of the flight plan
00.00	21	Not efficient[4]
03.00	17	Not efficient
06.00	12	1 hour 14 minutes
09.00	5	1 hour
12.00	1	28 minutes
15.00	8	52 minutes
18.00	14	1 hour 22 minutes
21.00	16	Not efficient
23.00	20	Not efficient

Table 4.1: Flight plan information for route *NEXAS-ZANKO* at different hours of the day (with an Airbus A320).

With respect to the computational time, it is seen that for the small-scale model of the Iberian Peninsula, each iteration takes around 2-3 seconds to be completed. This pattern should be maintained in a higher scale model, so that the total calculation time for each flight will depend basically on how far are the origin and destination waypoints and at which hour does the flight start. In any case, it can be stated that the computational time is acceptable.

[4]Not efficient means that the duration of the flight plan is higher than 1 hour 30 minutes.

Chapter 5

Further work and conclusions

5.1 Further work

After developing the different features of the flight planning tool, some areas of improvement which would enhance the model have been identified, so that they should be suitable for future researches and studies related to this work.

These improvements are mainly dedicated to provide completeness and consistence to the algorithm created, and would serve to offer to the user a better optimization solution.

5.1.1 Overflight costs

The overflight costs is another factor that determines the selection of different routes within the European airspace, together with the different ones that have been developed previously on this work.

This factor is mainly dependent on the different charging zones that can be found throughout the European airspace. These zones are defined mainly following country-related criteria, and in each of them, different charging policies are followed. Therefore, the variability on the costs of overflying one zone or another supposes that airlines may select different routes to have less total en-route charges.

However, this could provoke the selection of a larger en-route travel to avoid expensive charging zones, and that would mean a higher fuel consumption, so that a trade-off must exist between all the variables analysed.

Therefore, the fact of offering to the user the possibility of quantifying this trade-off between distance, time (both of them already offered) and overflight costs supposes an important feature which would mean a great quality upgrade to the flight planning tool.

To know better how this could be accomplished, it must be known that each aircraft operator is charged for using the air navigation services[1] needed to ensure that the aircraft is safely and efficiently guided in the airspace. EUROCONTROL, and most particularly, the Central Route Charging Office, is the agent responsible of collecting all the charges incurred by airlines and of distributing the correspondent money to each member state.

As EUROCONTROL states (see [28]), the overflight cost of each specific flight is determined by three different variables: the distance covered in each zone, the weight factor incurred and the unit rate of each specific sector. The general formula for calculating the overflight cost for a specific sector is defined as:

$$r_i = d_i \cdot p \cdot t_i \tag{5.1}$$

It must be borne in mind that the total en-route charges for a flight will be the sum of the overflight costs over all the different sectors that it has visited. In equation (5.1), the different elements should be explained.

The distance factor d_i is equivalent to one hundredth of the great circle distance (in kilometers) between the point of entry and the point of exit from a charging zone. These points are defined as the locations at which the lateral limits of the charging zones are crossed.

The weight factor p is dependent on the Maximum Take-Off Weight (MTOW) of the aircraft (measured in metric tonnes), and is defined as:

$$p = \sqrt{\frac{MTOW}{50}} \tag{5.2}$$

Finally, the unit rates or tariffs of en-route and terminal charges (t_i) are established by each independent EUROCONTROL member state for its sovereign airspace. Therefore, there exist different unit rates for each country. This is the factor that supposes that an optimization based on en-route costs can exist. These unit rates are defined yearly and adjusted monthly by each country, and they can be consulted on [29].

The actual influence of these overflight costs on the selection of routes by real airlines is analysed in [30]. With this information, it can be understood how the selection of a flight route depending on the charging zone is a relevant factor that influences strongly the economical outcome of each airline operating within the European airspace.

The way in which this feature could be introduced into the algorithm would have different steps. Firstly, the different charging zones should be defined into the model through the coordinates determining their shape, and that are

[1] Therefore, it must be understood that these route charges constitute a remuneration for the costs incurred by the states and the air navigation service providers for the en-route services. These costs include everything related to the provision of services (ATC, MET, AIS and more), regulatory services (the states) and to international agreements (mainly, EUROCONTROL).

specified in the AIP of each country. Together with this, a classification of each waypoint depending on to which zones do they belong should be carried out.

Then, the weight of the segments needed to define the Dijkstra's algorithm should be based on the route charge formula seen in equation (5.1). This would mean that a further input should be asked to the user of the program, the MTOW of the aircraft, allowing further customization and completeness of the flight plan.

In this way, the selection of one airway or another would be determined by its increase on the en-route costs.

The principal problem with this approach, and that has been encountered when its application was attempted, is the difficulty on determining the actual distance covered when an airway connects one charging zone with another. It is complicated to calculate with accuracy how many kilometers are travelled in this kind of connections, and as the route charge formula depends directly on the distance covered in each sector, this problem conditions noticeably the results.

Therefore, a different approach may be carried out to encounter a solution to this conflicting connections, and then, a consistent flight planning tool which offers the possibility of optimizing in terms of overflight costs could be developed.

5.1.2 Inclusion of standard arrival and departure phases

The algorithm has been developed to consider only the cruise phase of each flight. In section 1.6, it was explained that both the climb and descent phases are normally very tightly controlled through the establishment of standard departures (SID) and arrival (STAR) protocols, and therefore, the optimization in this case would be limited.

However, the consideration of these phases would become an important matter when the weather conditions, and more specifically, the wind, is being taken into account. In Chapter 3, it was seen how to compute the crosswind component, a very influencing factor when the aircraft has to take-off or land.

This is because strong crosswind components (as well as tailwinds) can limit, or even preclude, the possibility of taking-off or landing in a determined runway direction. That would mean that the aircraft would have to follow different standard protocols in order to be able to depart or arrive to a particular airport, as normally each airport establishes SID and STAR procedures for the different runways under use.

Therefore, the fact of taking these phases into consideration would mean that first, the complete flight is being taken into consideration, which is more attractive to any user. Secondly, a further optimization could be carried out related to which runway should be chosen for each operation and which procedures should be followed to reach the cruise phase.

Another benefit, principally regarding the optimization in terms of time, is that the time that has to be introduced by the user as starting flight hour would be fit better as the approximated taking-off time, and not as the starting time of the cruise phase. This would enhance the accuracy of the model, and would help to obtain solutions that should be more adapted to each user.

5.1.3 Consideration of the vertical profile

The principal limitation of the model proposed in this work is that the flight planning tool developed only takes into consideration the horizontal profile of the aircraft. As it has been explained previously, the optimization of this profile yields many benefits for the operator of the aircraft in terms of reduction of time-based costs, fuel and emissions.

However, a wide area of improvement for these reductions is found when considering the vertical profile. A consistent flight plan tool would calculate the optimum flight path when optimizing the lateral profile, and then it would combine it by computing the adequate velocities and flight levels for each phase of the flight. This could be implemented within the model, or even an external optimization tool could be applied to the program's output, as knowing the sequence of waypoints to be followed, the optimum velocities or flight levels to be used could be computed.

Currently, there are many researches related to the optimization of the vertical profile of aircraft, mainly related to the use of different flight levels during cruise phases (see [31]) or to the acquisition of optimum cruise velocities (see [32]). In further researches, it has been shown the potential benefits that could be obtained through the optimization of the different variables affecting the vertical profile of the aircraft, principally related to a relevant reduction in the consumption of fuel (see [33]) or to a reduction in the climate impact (see [34]).

Therefore, it can be stated that the consideration of the vertical profile inside the optimization process is one of the most relevant areas of improvement for the model proposed in this work, as the enhancement that it would introduce to the solutions produced by the algorithm would be very attractive to the users of flight planning tools.

5.1.4 Introduction of further weather conditions

Apart from the wind, which is already implemented in the algorithm, there are further weather conditions that affect the performance of a flight, as the temperature, the visibility, or the presence of clouds or storms.

The influence of these weather conditions is difficult to be determined in the cruise phase of a flight, and it would be mainly related to a variability in fuel consumption (depending on the temperature) or to the necessity of rerouting (due to really adverse weather conditions). Therefore, for the flight planning phase it is difficult to account for these variables in the cruise phase.

However, for take-off and landing, the inclusion of the METAR information on the airports could be an interesting feature to be implemented. These forecasts could help in the determination of the optimum runway and procedures to depart and land, and together with the improvement proposed in section

5.1.2, would complete the optimization of the initial and final phases of the flight.

5.2 Conclusions

Gathering the analyses carried out during the different phases of this work, various conclusions can be extracted, and they could be summed up to be:

- An efficient and consistent flight plan tool has been developed which is capable of effectively optimizing a desired flight route in terms of distance and time.
- Although not all the restrictions implemented in the model come from real data, the created program is prepared to compute an optimum route between an origin and a destination which complies with the majority of applying regulations on the European airspace. The solutions proposed would only be subjected to changes in the tactical and pre-tactical terms due to air traffic control issues.
- The computational time taken by the program to provide an efficient solution has been kept in acceptable terms, which was considered a necessary feature in order to develop an actually usable program.
- The fact that the user can personalize the input needed by the program makes it user-friendly, as it has the capacity to adapt in some ways to the necessities of the user, which was stated as a relevant feature to be implemented.
- The wind has been introduced as a weather condition playing an important role in the optimization of any flight route, adjusting better the model to real situations.
- Through the development of this program, the two more relevant concepts that have been understood are:
    1. The way in which the European airspace is currently being used and regulated, so that an exhaustive comprehension of the functioning of the whole air traffic management and control systems was achieved.
    2. The existence of a trade-off between the different variables affecting the economical efficiency of a flight, and how each of them affects and determines the different aspects relevant for aircraft operators, as fuel consumption or time-based costs.

Appendices

Appendix A

Project Budget

In this section, an estimation of the total cost necessary for the execution of this work is presented.

To assess it, it must be taken into account the global time spent in the documentation, programming and testing of the program created, together with the cost of all the tools needed for its development.

The project started in February 2015 and it has been finished on September 2015. The first phase, which was extended during two months, was dedicated to the documentation and acquisition of the data needed to support the development of the program.

Then, the implementation of the all the features previously seen were distributed among different phases. All of them can be observed in the following table.

	Work	**Hours**
Phase 1	Acquisition of data	90
Phase 2	Creation of the algorithm	100
Phase 3	Optimization in terms of distance	75
Phase 4	Optimization in terms of time	110
Phase 5	Implementation of schedules	55
Phase 6	Future researches and documentation	50
Total		480

Table A.1: Time spent on the different phases of the project.

Knowing the number of hours spent on the project, the cost of the personal work can be obtained applying an engineer salary of 20 €/h, so that is supposes a total of 9,600 €. To obtain the total cost of the project, also the material costs incurred during its development must be taken into account. This basically sums up to the computer and the MATLAB license costs. All of them, together with the total cost, can be seen in Table A.2.

Concept	**Cost (€)**
Personal costs	9,600
Computer	800
MATLAB software	4,000
Total	**14,400**

Table A.2: Project Budget.

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